PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

PARE

CHAPTER 4

Protecting the environment and the energy supply

Final Report

WWW.PAREPROJECT.EU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 769220. This publication [communication] reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Table of Contents

List of Figures 3

List of Tables 8

Chapter 4 - Protecting the environment and the energy supply.. 10

4.1 Reduction of Noise and Emissions 30

4.1.1. Engine Noise for Turbofans and Propfans 39

4.1.2. Aerodynamic Noise 74

4.1.3. Noise Abatement Operating Procedures 78

4.1.4. Local Emissions of the aircraft 82

4.1.5. Cruise efficiency and global emissions 106

4.1.6. Carbon Offsetting and Reduction Scheme for International Aviation 135

4.1.7. Future SST environmental impact 142

4.1.8. Drones and urban air mobility 156

4.1.9. Electric aircraft 187

4.2 Emissions Free Taxying at Airports 213

4.3 Design and manufacture bearing in mind recycling 229

4.4 Sustainable Alternative Fuel Sources 238

4.5 Atmospheric Research, Weather and the Environment 250

List of Figures

Figure 4.1 - CAEP Timeline 11

Figure 4.2 - Conventional Fuel Consumption from Aviation, 2005 to 2050: a) International only; b) International plus Domestic 13

Figure 4.3 - Net 3.16 CO_2 Emissions from Aviation, 2005 to 2050: a) International only; b) International plus Domestic 13

Figure 4.4 - Net 3.16 CO_2 Emissions from International Aviation, 2005 to 2050, a) Including Alternative Fuels Life Cycle Emissions Reductions: b) Including Potential Replacement of Jet Fuel with Alternative Fuels 14

Figure 4.5 - Demand Uncertainty versus other Contributions (the CAEP/10 trends baseline is shown for comparison): a) Comparison of Conventional Fuel Consumption from International Aviation, 2005 to 2050; b) Comparison of Net 3.16 CO_2 Emissions from International Aviation, 2005 to 2050 14

Figure 4.6 NOx Emissions from Aviation, 2010 to 2050: a) International; b) Global (International plus Domestic), with comparison between CAEP/11 and CAEP/10 forecasting 16

Figure 4.7 - Total Aircraft Noise exposure assessment for 315 Airports, 2010 to 2050: a) Contour Area Above 55 dB DNL (km^2); b) Global Population Exposed to Noise Above 55 DNL 17

Figure 4.8. - NOx Emissions below 3000 ft from Aviation, 2010 to 2050: a) International; b) International plus Domestic 18

Figure 4.9 - PM Emissions below 3000 ft from Aviation, 2010 to 2050: a) International; b) International plus Domestic 18

Figure 4.10 -Number of flights increases by 42% between 2017 and 2040 under the base traffic forecast: a) forecasting from; b) forecasting from 19

Figure 4.11- Fleet renewal could stabilize average noise levels at today's 47 major airports by 2030 19

Figure 4.12 - Noise and emissions grow slower than passenger kilometres but emissions grow faster than number of flights 20

Figure 4.13 - CO_2 emissions are steadily increasing again since 2013 21

Figure 4.14 - NOx emissions will increase further, but advanced engine combustor technology could help curb their growth after 2030 22

Figure 4.15 - Global-level Analysis 23

Figure 4.16 - World international passenger traffic evolution 1945 – 2020 24

Figure 4.17 - V-shaped and U-shaped paths 25

Figure 4.18 - World's GDP Projections (by IMF) 25

Figure 4.19 - 9/11 and global financial crisis had a U/L-shaped impact on air transport in United States 26

Figure 4.20 -The goals and action areas for ACARE Challenge 3 in relation to fuel/energy consumption & GHG reduction along Sustainable Aviation Roadmap 2050 28

Figure 4.21 - Timeline for Challenge 3: Protecting the environment and the energy supply 29

Figure 4.22 - Main sources of engine and airframe noise 35

Figure 4.23 - Sources of acoustic emission during: a) takeoff; b) landing 35

Figure 4.24 - Improvement in aircraft efficiency 36

Figure 4.25 - ICAO requirement to aircraft noise and ACARE 2050goal 39

Figure 4.26 - Development of Quieter Rolls Royce Aircraft Engines 39

Figure 4.27 - Forecast Changes in UK Aviation Noise Output between 2010 and 2050 40

Figure 4.28 - Committed major national/regional initiatives as of end 2018 40

Figure 4.29 - MDOF hardware tested and noise measurements taken 41

Figure 4.30 - Typical directivity patterns and qualitative distribution of noise power between the main sources (a) in dependence with varying by passratio (b) of the turbofan engines 42

Figure 4.31 - Chevron nozzle: a) Boeing Quiet Technology Demonstrator nozzle made of shape memory material; b) Rolls-Royce/Airbus low interior noise fan nozzle 43

Figure 4.32 - Engine noise reduction technologies 44

Figure 4.33 - Chevron nozzle, type T-fan 45

Figure 4.34 - Pylon with blowing of gas to the stream 45

Figure 4.35 - Industry first 100% acoustic inlet on A380/Trent 900 46

Figure 4.36 - Roadmap of EU Aircraft Noise Research Projects vs Key Technical Areas (Generation 1 and 2 solutions - NRT1 and NRT2 performances – were achieved by results of the projects shown and classified in accordance with priority acoustic sources) 47

Figure 4.37 - ACARE SRA 1: Noise Goals for Fixed-Wing Aircraft 47

Figure 4.38 - X Noise Pioneering Technology Evaluation / Progress Assessment 48

Figure 4.39 - Technology Readiness Level Classification used for solutions assessment 49

Figure 4.40 - Expected advances on noise reduction with NRT1 and NRT2, as well as the Noise Abatement Procedure 49

Figure 4.41 - Noise Reduction Technologies Development & Validation 50

Figure 4.42 - The compliance of Rolls-Royce engines with modern ICAO requirements 51

Figure 4.43 - Rolls Royce engine noise reduction technologies 52

Figure 4.44 - Engine discrete noise sources and their reduction 52
Figure 4.45 - Engine broadband noise sources and their reduction 53
Figure 4.46 - Rolls Royce technology for the future engine 54
Figure 4.47 - Family of the AN-148 passenger regional aircraft and the AN-178 medium transport aircraft 57
Figure 4.48 - Noise of Current and 'Imminent' aircraft relative to Chapter 3 58
Figure 4.49 - Noise footprint for of new Generation 1 aircraft: a) A320neo; b) Boeing 787-8 59
Figure 4.50 - Comparison of US and EU research goals 60
Figure 4.51 - IEP2 predicted noise reduction target versus US and European research goals 60
Figure 4.52 - Typical fleet transition from current aircraft to 'Imminent' and 'Future' aircraft 61
Figure 4.53 - Programme Level & EPNL reduction for aircraft noise due to technology improvements 62
Figure 4.54 - Airbus views on a futuristic design for 2030 - future noise reduction technologies with contribution of engine/airframe installation effects 62
Figure 4.55 - Advantages of an open-rotor engine 62
Figure 4.56 - Design of Silent Aircraft SAX-40 involving key technologies of noise abatement 64
Figure 4.57 - Bypass ratio in different engine schemes 65
Figure 4.58 - Non-standard aircraft layouts 66
Figure 4.59 - Built-in PP layouts with spaced ducts 66
Figure 4.60 - Elements of numerical simulation 67
Figure 4.61 - Effectiveness of methods for reducing the noise level in the fan 72
Figure 4.62 - Effectiveness of methods for reducing the level of jet stream noise 73
Figure 4.63 - Key Japanese technology projects for Engine Noise reduction 73
Figure 4.64 - Installed jet noise investigations in RF aircraft noise programs 74
Figure 4.65 - Airframe noise reduction technologies 75
Figure 4.66 - Noise reduction potential of a slat cove cover, slat hook extension and slat cover filler 76
Figure 4.67 - Noise reduction potential of a slat acoustic liner on slat cove and main element and airfoil leading-edge strips 77
Figure 4.68 - Side-edge noise reduction using brush-type edge replacements and continuous moldline link 77
Figure 4.69 - Example of noise reduction potential of A340 full-scale main landing gear fairings 78
Figure 4.70 - Departure and approach noise abatement procedures 79
Figure 4.71 - Overview of most important non-acoustic factors contributing to aircraft noise annoyance 81
Figure 4.72 - Schematic presentation of emissions, dispersion, concentrations and impacts with their interaction at airport level 83
Figure 4.73 - Contribution of pollution sources in emissions in international airport Beijing in 2015 85
Figure 4.74 - Annual CO_2 emissions from civil air vehicles in China within the period 1960-2009 86
Figure 4.75 - Historical ICAO certification Standards together with the 2006 medium-term and long-term goals 89
Figure 4.76 - Improving average NOx margin to CAEP/6 limit for in-production engines shown in successive versions of the ICAO EEDB 89
Figure 4.77 - Illustration of ICAO emissions certification procedure in the LTO cycle 90
Figure 4.78 - 2009 Review data with RQL combustors in grey and new mid-OPR engines. Generation staged DLI combustors in red. Note these data points area mixture of certificated engines and high TRL developments 91
Figure 4.79 - Demonstrator SAFRAN "open rotor" 93
Figure 4.80 - Concept of TAPS dilution section 94
Figure 4.81 - Combustion chamber 5-sectional sector 95
Figure 4.82 - Three-sectional sector of low-emission combustion chamber at NASA ASCR bench (Pratt & Whitney) 96
Figure 4.83 - Goodrich multi-zone multi-stage LDI concept 97
Figure 4.84 - Woodward LDI package in 5-sectional sector 98
Figure 4.85 - LDI Woodward package undergoes tests with lean mixture 98
Figure 4.86 - Conceptual implementation of 3-zone module 98
Figure 4.87 - Spray test using Parker 3-zone probe 99
Figure 4.88 - Advanced Airbus Technologies 102
Figure 4.89 - The framework and development phases of the CO_2 Standard 105
Figure 4.90 - The CO_2 Standard regulatory limits for the aircraft 106
Figure 4.91 - Radiative forcing by emissions and drivers 108

Figure 4.92 - Updated schematic of the principal emissions from aviation operations and the relationship of emissions to climate change and impacts. The terminology, ΔX, indicates a change in component X. The term ΔClouds represents contrail induced cloudiness and aerosol-cloud interactions 109
Figure 4.93 - Global CO_2 emissions are still increasing (Global carbon project, 2019 update) 110
Figure 4.94 - Global temperature change may exceed 1.5°C in few decades 110
Figure 4.95 - Global aviation CO_2 forecast with ACARE assumption 111
Figure 4.96 - CO_2 Emissions Trends from International Aviation, 2005 to 2050 113
Figure 4.97 - Fuel Burn Trends from International Aviation, 2005 to 2050 113
Figure 4.98 - ATM improvements for fuel savingsby aircraft optimal flight profile 114
Figure 4.99 - NASA N+2 aircraft generation 115
Figure 4.100 - Annual global fuel consumption for all simulated scenarios 117
Figure 4.101 - Annual projected fuel consumption by region 117
Figure 4.102 - Annual fuel consumption for selected countries 117
Figure 4.103 - Annual fuel consumption for Scenario 3 118
Figure 4.104 - Annual emission reductions in the LTO cycle between scenarios 1.5 and 3 118
Figure 4.105 - Annual CO_2 emissions produced by commercial aviation for all scenarios 119
Figure 4.106 - Annual CO_2 emissions produced by the regions of the world according to Scenario 3 119
Figure 4.107 - Annual CO_2 emissions for selected countries under Scenario 3 120
Figure 4.108 - Annual CO_2 emissions calculated for each 1 × 1 cell for Scenario 3 120
Figure 4.109 - Comparison of normalized fuel consumption tendencies for scenarios 1.5, 2, 3 and the goal of ICAO: 2% global annual increase in fuel efficiency 121
Figure 4.110 - Next-generation aircraft types and associated "benefits" in fuel efficiency 123
Figure 4.111 - Forecast of fuel consumption by the aircraft fleet from 2008 to 2050 for basic and conservative scenarios 1-4 125
Figure 4.112 - Forecast of fuel consumption for the aircraft fleet for the scenarios under study and the target ATAG level period 2008 to 2050 126
Figure 4.113 - Estimated excess CO_2 emissions per flight are decreasing in taxi, take-off, climb/descent and en route phases] 126
Figure 4.114 - ACARE CO_2& NOx goals calendar (using CAEP6 margin for NOx) 128
Figure 4.115 - Three “in-sector reduction streams” aligned with the Global Coalition for Sustainable Aviation 130
Figure 4.116 - Energy consumption by transportation sector 135
Figure 4.117 - A key barrier to SAF uptake is their higher cost than fossil jet fuel 131
Figure 4.118 - Prospects of direct electrification of the aircraft of various flight range 133
Figure 4.119 - Hydrogen fueled planes 134
Figure 4.120 - Explore the feasibility of a long term aspirational goal 135
Figure 4.121 - Strong synergies in basket of measures to control CO_2 emission in aviation sector 136
Figure 4.122 - Phases of CORSIA implementation 137
Figure 4.123 - Calculation CO_2 offering requirements 138
Figure 4.124 - CORSIA route-based approach 138
Figure 4.125 - World map show in green the States which have volunteered in CORISA (1 September 2019) and in yellow the States from/to which flights are expected to be exempt after 2027 142
Figure 4.126 - Great cycle distance between major cities 143
Figure 4.127 - Potential size of the supersonic passenger market 143
Figure 4.128 - Potential size of the supersonic passenger market 144
Figure 4.129 - Illustration of the industrial and academic activities on supersonic aircraft around the world by NASA 144
Figure 4.130 – NASA Roadmap for supersonic activities 145
Figure 4.131 – List of EC funded projects on civil supersonic aviation in the last 20 years 146
Figure 4.132 – Radiative forcing from aircraft in 2050 with supersonic fleet 147
Figure 4.133 – Three classes of concepts for SST 2.0 in EU projects during 2000…2020 147
Figure 4.134 – Various configuration concepts for supersonic aircraft 148
Figure 4.135 – Relationship of signature shapes to vehicle area development 148
Figure 4.136 – SSBJ community noise requirements 149
Figure 4.137 – 80 dB Sound exposure level contours for 75-tonne aircraft just meeting the various ICAO chapter limits 150
Figure 4.138 – HISAC low LTO noise platform (Team A) 150

Figure 4.139 – Example of a mixer-ejector concept tested at the ONERA Cepra19 wind tunnel 153
Figure 4.140 – CVC concept with an axially translating mixer (left: TO configuration, right: cruise configuration) 154
Figure 4.141 – Results of the jet noise model developed in HISAC by ISVR and comparison with Cepra19 noise measurements 154
Figure 4.142 – HISAC reference aircraft shape for the evaluation of LTO noise levels 155
Figure 4.143 – Comparison between conventional ground based (red line) and air transportation (white dashed line) for connection Manhattan and JFL airport in New-York city 157
Figure 4.144 – Integrated Aviation System architecture framework 158
Figure 4.145 – Percent of UAM trips captured for ten focus urban areas 159
Figure 4.146 – Advanced aerial mobility covers a diverse set of stakeholders, deployment environments and use cases, not limited to urban air mobility 159
Figure 4.147 – UAS Traffic Management Architecture – 5G Connections & communications are internet-based & built on industry standards & protocols 160
Figure 4.148 – Global drone market size and forecast 2018-2024 162
Figure 4.149 – Factors in both the aircraft fleet and pilot population inhibited general aviation's progress and scale 164
Figure 4.150 - A rendering of the Airbus/Audi modular Pop.Up, with wheelbase and rotor attachments (Ital Design) 164
Figure 4.151 - Sample scenario for eVTOL operations in each of the four cities targeted as part of the study 165
Figure 4.152 – GL-10 UAS DEP Tilt-Wing Tilt-Tail VTOL Flight Demonstrator 170
Figure 4.153 – Battery weight as function of range 171
Figure 4.154 – An overview of the power density of electric motor concepts from suppliers with aviation activities compared to aviation certified piston engine or turbine application 172
Figure 4.155 – Comparative characteristics of electrical machines and gas turbine engines 172
Figure 4.156 – First order noise impact modeling for UAV noise assessment 173
Figure 4.157 – Noise Power Distance for small helicopters in AEDT data base 174
Figure 4.158 – Noise level comparisons for arrival and departure mode 174
Figure 4.159 – Large percentage of operations are in the areas of low background noise 175
Figure 4.160 – Well-to-wake greenhouse gas (GHG) emissions 175
Figure 4.161 – Notional dependence of ODM constraints on network density 176
Figure 4.162 – Regulatory pathways through which aircraft noise may result in operational restrictions for aircraft operators. Image developed from information in the FAA Airport Compliance Manual and the 1976 Aviation Noise Abatement Policy III.3.a-e 177
Figure 4.163 – Wake geometry of quadrotor and side-by-side aircraft at cruise speed 179
Figure 4.164 – Low noise trajectories for R-44 helicopter 183
Figure 4.165 – NASA UAV/UAM Noise Research Roadmap 183
Figure 4.166 – Penetration of electrical systems by aircraft type 187
Figure 4.167 – Electrical power generating capacity by introduction year 188
Figure 4.168 – Overview of the All-Electric Aircraft system 189
Figure 4.169 – A timeline of achievement in electric propulsion 191
Figure 4.170 – Trends of possible aircraft hybrid architectures at different installed power 192
Figure 4.171 – The plans of Airbus for creating an electric aeroplane 192
Figure 4.172 – Project of E-Fan X 192
Figure 4.173 – E-Fan X wind tunnel testing 193
Figure 4.174 – The plans of Airbus for creating an electric aeroplane 194
Figure 4.175 – Roadmap for more and all-electric aircraft in view of Safran 195
Figure 4.176 – Vahana technical specifications 195
Figure 4.177 – CityAirbus technical specifications 196
Figure 4.178 – Projects of aeroplanes with distributed propulsion systems and boundary layer suction 197
Figure 4.179 – Timeline of expected future fuel efficiency improvements compared to predecessor aircraft or engine of the same category 198
Figure 4.180 – Fuel burn reduction expectation with respect to year 2000 200
Figure 4.181 –Illustration of the UHB Fan Model identifying the locations of two noise reduction technologies used during the NASA Ultra High Bypass Fan Noise Reduction Test, which were Over-the-Rotor acoustic treatment and Soft Stator Vanes 204
Figure 4.182 – Open Rotor mounted on Hera vehicle (Snecma) and under test at the S1 Onera wind tunnel and the simulation of interactions between the two propellers (Onera) 205
Figure 4.183 – Further ACARE objectives for 2050 206
Figure 4.184 – Expected sequence of future aircraft generations in different seat categories, including recent indications on new developments 211

Figure 4.185 – NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 9 "Reduction of Noise and Emissions" 212
Figure 4.186 – The proposed categorisation of alternative taxiing solutions 214
Figure 4.187 – A generic system architecture for both (a) external and (b) onboard ETSs 215
Figure 4.188 – Examples of external electric taxiing systems: (a) Tesla-X towing the empty Boeing 787-9 with a mass of 130,000 kg; (b) TaxiBot at Frankfurt airport 219
Figure 4.189 – WheelTug system implemented in NG 219
Figure 4.190 – Motor Developed by DLR 219
Figure 4.191 – Demonstration of EGTS from Safran: a) first electric taxiing solution; b) demonstartion on A-320 220
Figure 4.192 – Specification sheet for the Panasonic NRC 18650 223
Figure 4.193 – Specification of the Panasonic NRC18650 battery 224
Figure 4.194 – NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 10 "Emissions Free Taxiing at Airports" 229
Figure 4.195 – Boeing-787 relaunched the Li-ion battery system with the new design, adding an extra weight of 68kg to the weight of the aeroplane 234
Figure 4.196 – Use of batteries in a typical aircraft 235
Figure 4.197 – Batteries in the cabin of an airliner 236
Figure 4.198 – Cargo with batteries that can cause safety risks 237
Figure 4.199 – NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 11 "Design and manufacture bearing in mind recycling" 237
Figure 4.200 – Results of investigations to the Alternative Aviation Fuel Experiment 243
Figure 4.201 – The results of investigations to the Alternative Aviation Fuel Experiment program 243
Figure 4.202 – The results of strict policy investigations to the Alternative Aviation Fuel Experiment (AAFEX) program 244
Figure 4.203 – Predictive appraisal of accomplishing the ecological objectives 2050 245
Figure 4.204 – Biofuelprice forecast 246
Figure 4.205– Biofuel emissions over the life cycle 246
Figure 4.206 – ACARE Flightpath 2050 Goal 13 248
Figure 4.207 - NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 12 "Sustainable Alternative Fuel Sources" 249
Figure 4.208 – Benchmarks for goal 13 253
Figure 4.209 – Environmental issues effects by region 260
Figure 4.210 – Environmental issues impacts on aviation by region 261
Figure 4.211 – The Sentinel families of European environmental satellites 263
Figure 4.212 – Maturity Plan for the Sentinel family 264
Figure 4.213 – Cosmic microsatellite system 264
Figure 4.214 – Convective initiation 266
Figure 4.215 – Turbulence Detection 266
Figure 4.216 – Oceanic Weather 266
Figure 4.217 – Cloud properties 267
Figure 4.218 – Volcanic Ash 267
Figure 4.219 – Winds 267
Figure 4.220 – Successive generation of EUMETSAT 268
Figure 4.221 – Meteosat Third Generation Satellite Maturity Plan 269
Figure 4.222 – Polar System Second Generation (EPS-SG) Projection 269
Figure 4.223 – Image obtained by several environmental satellite system 270
Figure 4.224 – Instrumentation installed in aircraft for environmental purpose 271
Figure 4.225 – Expected growth in the size of the fleet of aircraft equipped with IAGOS instrumentation 272
Figure 4.226 – An UAV designed for environmental monitoring in hazardous conditions 274
Figure 4.227 – Weather alert available for aviation 276
Figure 4.228 – NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 13 "Atmospheric Research, Weather and the Environment" 277

List of Tables

Table 4.1 – CAEP/11 Environment Trends: Fuel and NOx Emissions Scenarios Summary 15
Table 4.2 – Scope of CAEP/11 Noise Trends Assessment 17
Table 4.3 – The action areas for *Challenge 3* of the ACARE perspectives 27
Table 4.4 – Comparison of long-term goals for environmental impact factors of aviation between the Policy of ICAO, EU and USA on Research and Development 28
Table 4.5 - Global strategies for reducing aviation fuel uses and emissions 30
Table 4.6 - New generation aircraft recently introduced or about to enter the market (before the end of 2020) 32
Table 4.7 - Airframe technologies development impact and expected availability for introduction 33
Table 4.8 - Engine technologies development impact and expected availability for introduction 34
Table 4.9 - Technology Factors Airframe and Aircraft Engine 34
Table 4.10 - Examples of potential noise reduction through component improvements 36
Table 4.11 - NASA AATT technology objectives 41
Table 4.12 - Inlet measured component noise reduction 41
Table 4.13 - Technology Readiness Level and Technology Status 50
Table 4.14 - Noise of Current and 'Imminent' aircraft relative to Chapter 3 58
Table 4.15 - CAEP IEP2 Aircraft Noise Goals for short-medium (2020) and long (2030) term 60
Table 4.16 - Emissions in Beijing airport 85
Table 4.17 - APU emissions 85
Table 4.18 - Comparative data on emissions in big airports of the world 86
Table 4.19 - Level of understanding in airport emission inventory: green (good); yellow (fair); red (poor) 87
Table 4.20 - NO_x emission level of GE 5-head section for ICAO LTO cycle 95
Table 4.21 - Noise level of traditional and adaptive (morphing) wings in the air tunnel 101
Table 4.22 - FORUM-AE assessment against ACARE emissions goals 112
Table 4.23 - Aircraft fuel-efficiency improvement till 2020 intermidiate goal 114
Table 4.24 - Stepwise goal for aircraft CO_2 reduction between 2020–2050 114
Table 4.25 - Opportunities for fuel savings by character aircraft groups 115
Table 4.26 - The results of modelling the annual global fuel consumption (in billions of kilograms for all scenarios) 116
Table 4.27 - Ongoing and potential future mitigation measures 136
Table 4.28 - NASA-developed Concept Vehicles for UAM 166
Table 4.29 – Safran-developed UAM Vehicles performances 167
Table 4.30 - Different use-cases are a key driver behind the broad conceptual diversification of the eVTOL aircraft landscape 170
Table 4.31 - Technology-based ODM aircraft noise reduction proposals 177
Table 4.32 - Noise reduction operations enhanced by potential ODM aircraft capabilities 182
Table 4.33 - Electrical propulsion architectures 190
Table 4.34 - Electric systems and battery requirements for electric aircraft architectures 199
Table 4.35 - Comparison of different types of battery chemistries 216
Table 4.36 - Details of batteries used in different aircraft 216
Table 4.37 - Comparison of Li-ion and Ni-Cd aircraft grade batteries 217
Table 4.38 - Summary of the main (Automotive) Lithium-ion types / State of the art 217
Table 4.39 - Comparison of different types of battery chemistries 222
Table 4.40 - Some characteristics of commercially available secondary lithium-ion cell, ordered by specific energy 224
Table 4.41 - Deficiencies of present lithium ion batteries and possible remedies 226
Table 4.42 - Comparison of different cell chemistries used in aeronautics 231
Table 4.43 - Details of batteries used in different aircraft 232
Table 4.44 - Objectives, tasks, and milestones of European Advanced Biofuels Flightpath 239
Table 4.45 - Possible pathways to obtain ATJ biofuel. Source "2 million tons per year: A performing biofuels supply chain for EU aviation - August 2013 Update 250
Table 4.46 - Some climate change effects 254
Table 4.47 - Endangered species and ecosystem 254
Table 4.48 - Waste generation and management 254
Table 4.49 - Water and Air quality 255
Table 4.50 - Climate risks and their impact 255
Table 4.51 - Environmental issues and their implications for aviation 260
Table 4.52 - Effects of climate change on aviation 262

Table 4.53: Capabilities expected of an UAV designed for environmental monitoring

Chapter 4 - Protecting the environment and the energy supply

Environmental protection is and will continue to be a key driver for the aviation industry as a whole. The challenge concerning the environment is to reduce continuously the environmental impact in the face of continuing expansion in demand for aviation. This expansion will also put pressure on existing energy supplies. Towards 2050, the forecast growth in the aviation industry will drive the need to deliver revolutionary technology solutions at an increasing rate and secure the path to sustainable energy supplies that can displace today's fossil fuels to mitigate fully the potential impact on the atmosphere. This set of 5 goals consists of reductions of noise and emissions (section 4.1), emissions-free taxiing (section 4.2), recycling enabled by design (section 4.3), alternative fuels (section 4.4) and atmospheric research (section 4.5). The goals of *Flightpath 2050* in the field:

1. In 2050 technologies and procedures available allow a ***75% reduction in CO_2*** emissions per passenger kilometre and a ***90% reduction in NOx emissions***. The ***perceived noise emission of flying aircraft is reduced by 65%.*** These are relative to the capabilities of typical new aircraft in 2000.

2. ***Aircraft movements are emission-free when taxiing***.

3. ***Air vehicles are designed and manufactured to be recyclable***.

4. ***Europe is established as a centre of excellence on sustainable alternative fuels***, including those for aviation, based on a strong European energy policy.

5. ***Europe is at the forefront of atmospheric research*** and takes the lead in the formulation of a prioritised environmental action plan and establishment of global environmental standards.

Aviation environmental impacts include gaseous emissions and noise issues [ICAO Resolution A40-17, 2019]. ACARE runs three research projects to assess the achievements towards these goals: X-Noise EV [X-NOISE, 2015], which relates to aviation noise research, Forum AE [FORUM - AE, 2015], which relates to emissions research, and Core-Jet Fuel [CORE-JETFUEL, 2016], which relates to alternative aviation fuels. In 2015 ACARE published a 2014/2015 activity update. These update reports on the progress of each of these projects including an assessment of performance against ACARE's goals. The report concludes that noise research is on track to meet its target, that significant work is required to meet the emissions targets, specifically technology maturation, and that a quantitative target is required at European level for alternative fuels.

There is a shared awareness, at least politically, that climate change will dramatically modify our societies in the longer term. The image of Air Transport in the public mind has been tarnished by its perceived impact on the environment. The main levy to reduce aviation emissions will be to reduce travel demand through taxes and/or individual emissions quotas. Hardly any technical solution can reduce both types of impact. Trade-off decisions have to be made by all industry actors. The potentially negative impact of any drastic "green" approach on the supply industry is a concern. There is a need for global agreements on such measure to maintain fair competition.

ICAO, as the lead United Nations (UN) Agency in matters involving international civil aviation, is conscious of and will continue to address the adverse environmental impacts that may be related to civil aviation activity and acknowledges its responsibility and that of its Member States to achieve maximum compatibility between the safe and orderly development of civil aviation and the quality of the environment. In carrying out its responsibilities, ICAO and its Member States will strive to [ICAO Resolution A40-17, 2019]:

a) Limit or reduce the number of people affected by significant aircraft noise;

b) Limit or reduce the impact of aviation emissions on local air quality; and

c) Limit or reduce the impact of aviation greenhouse gas emissions on the global climate.

In 2008 the global stakeholder associations of the aviation industry (Airports Council International, Civil Air Navigation Services Organization, International Air Transport Association and International Coordinating Council of Aerospace Industries Association), under the umbrella of the Air Transport Action Group, committed to addressing the global challenge of climate change and adopted a set of ambitious targets to mitigate CO_2 emissions from air transport:

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020;
- A cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth);
- A reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 levels.

To achieve these targets, all stakeholders agreed to closely work together along with a four-pillar strategy:

- Improved technology, including the deployment of sustainable low-carbon fuels;
- More efficient aircraft operations;
- Infrastructure improvements, including modernized air traffic management systems;
- A single global market-based measure, to fill the remaining emissions gap.

For that latest ICAO Assembly adopted three environmental resolutions [ICAO Resolution A40-17, ICAO Resolution A40-18, ICAO Resolution A40-19, 2019], providing in such way very ambitious policy for environment protection from civil aviation impact and for the sustainable growth of aviation as an important element for future economic growth and development (ICAO contributes to ten of 17 United Nations Sustainable Development Goals). ICAO has established a Committee on Aviation Environmental Protection (CAEP) 50 years ago (it was called Committee on Aircraft Noise – CAN) to assist in the further development of Standards, Recommended Practices and Procedures and/or guidance material (SARPs) on aircraft noise and engine emissions to assist States in implementing them in an efficient way (Figure 4.1).

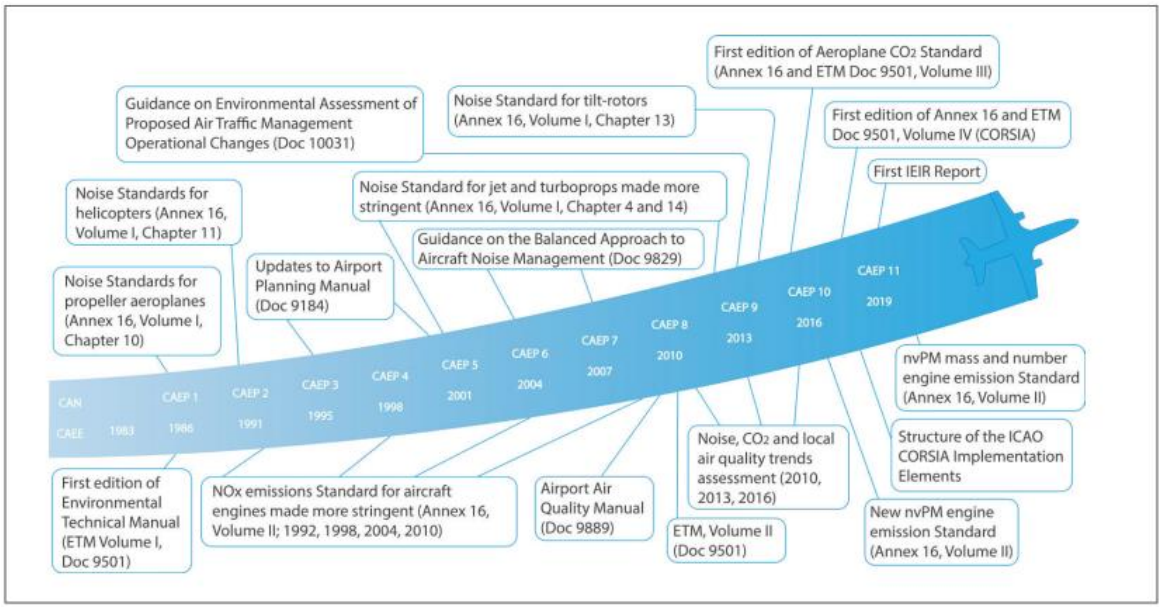


Figure 4.1: CAEP Timeline

The most significant and demanding deliverables from CAEP are reflected in the international SARPs contained in Annex 16 to the Convention on International Civil Aviation. These encompass aircraft noise (Annex 16, Volume I), aircraft engine emissions (Annex 16, Volume II), aeroplane CO_2 emissions (Annex 16, Volume III), and, most recently, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) contained in Annex 16, Volume IV [ICAO Annex 16, 2019]. These SARPs were developed by means of a technically-driven and consensus-based approach, with effective cooperation between ICAO Member States, industry, relevant aviation stakeholders and civil society. All these SARPs are kept up-to-date, ensuring that the latest environmental technologies are incorporated into new aircraft designs, and the environmental impact of international civil aviation is limited and reduced.

The most recent meeting of CAEP, the 11th CAEP Meeting (CAEP/11) took place in ICAO Headquarters in Montréal in February 2019. The meeting agreed, inter alia, on new non-volatile particulate matter (nvPM) mass and number standards, new integrated noise and emissions technology goals for the sector. The meeting also considered technical details associated with the consideration of CORSIA eligible fuels, a global synthesis on climate change adaptation and aircraft end-of-life and recycling. It also considered an eco-airports toolkit e-collection, community engagement for Performance-Based Navigation (PBN), and the environmental analysis of the ICAO Aviation System Block Upgrades (ASBU), amongst many other items to address aircraft noise and emissions. Moving into the future, CAEP will continue to monitor the developments and new emerging issues in aviation environmental protection, to take necessary actions, and make well-considered recommendations to the ICAO Council, in a timely manner. A number of ICAO Documents produced to support the Standards [ICAO Annex 16, 2019], Environmental Technical Manual [ICAO Doc 9501, 2019] is most important, all of them compound a total SARP for environment protection purposes in the civil aviation sector, their implementation in Member States is necessary to achieve the ICAO Goals, so as the EU FlightPath 2050 Goals.

The environmental trends, usually discussed at CAEP meetings and available for public from ICAO Environment Reports [ICAO Environmental Report 2019] are based on the latest air travel demand forecast data, using the base year of 2015 (in the current case from CAEP/11 meeting). Forecast years were 2025, 2035, and 2045, and results were then extrapolated to 2050. Fuel burn and emissions results are for international aviation only, while noise trends include both domestic and international operations. In 2015, approximately 65 per cent of global aviation fuel consumption was from international aviation. This proportion is expected to remain relatively stable out to 2050. Such trends can be affected substantially by a wide range of factors such as fluctuations in fuel prices and global economic conditions.

Conventional fuel consumption and net 3.16 CO_2 emissions from international and international plus domestic aviation are shown in Figures 4.2 and 4.3 respectively. By 2045, fuel consumption is projected to have increased 2.2, or 3.1 times the 2015 value, while revenue tonne-kilometres are expected to increase 3.3 times under the most recent forecasts. Extrapolating to 2050, fuel consumption is projected to increase 2.4 to 3.8 times the 2015 value, while revenue tonne-kilometres are expected to increase 3.9 times. Depending upon the scenario, technology improvements could provide an additional 157 Mt reduction in fuel consumption (Figure 4.2) and 497 Mt reduction in CO_2 emissions (Figure 4.3) in 2050. Operational improvements are smaller than those that could be realized by technology, namely up to an additional 57 Mt reduction in fuel consumption and 183 Mt reduction in CO_2 emissions in 2050.

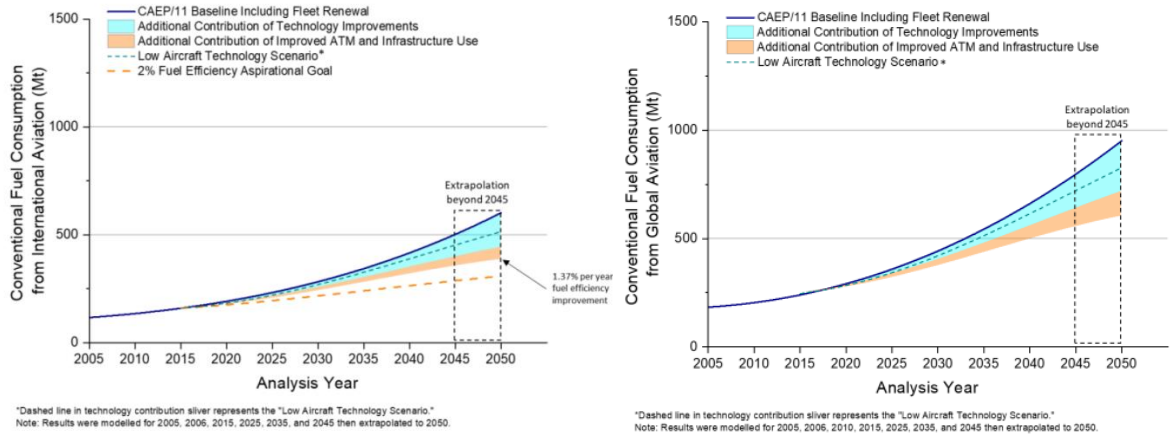


Figure 4.2: Conventional Fuel Consumption from Aviation, 2005 to 2050: a) International only; b) International plus Domestic [ICAO Environmental Report 2019]

The trends assessment for international aviation shows the full range of results from CAEP's Alternative Fuels Task Force (AFTF), including the full replacement of conventional fuel with sustainable aviation fuel (SAF) by 2050, as well as an "illustrative" case. CAEP/AFTF was charged with calculating estimates of SAF contributions to fuel replacement and life cycle GHG emissions reductions in conducting its trends assessment out to 2050. See Figure 4.4a) for GHG emissions results and Figure 4.4b) – for fuel replacement results. The amount of SAF and the associated GHG emissions reductions were allocated proportionally between international and domestic use based on projected fuel demand (roughly 60/40, respectively).

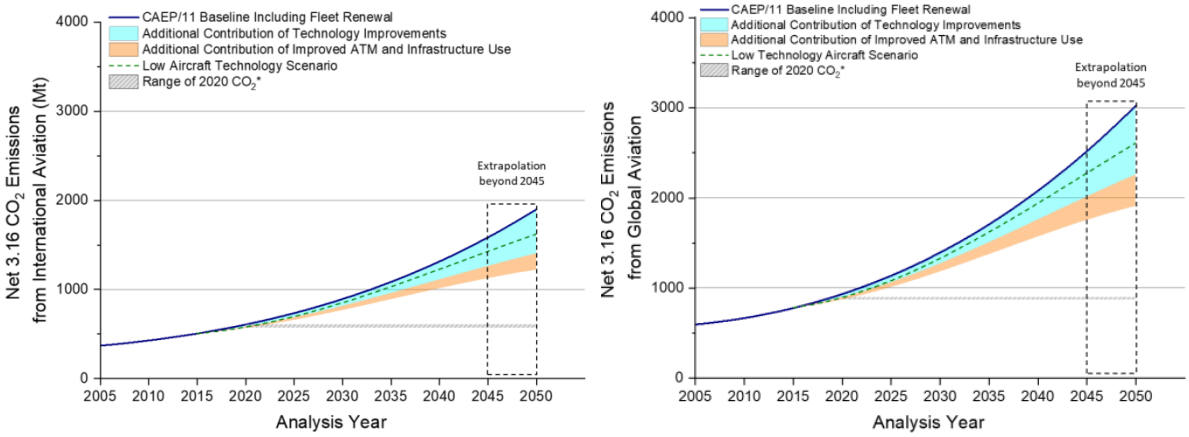
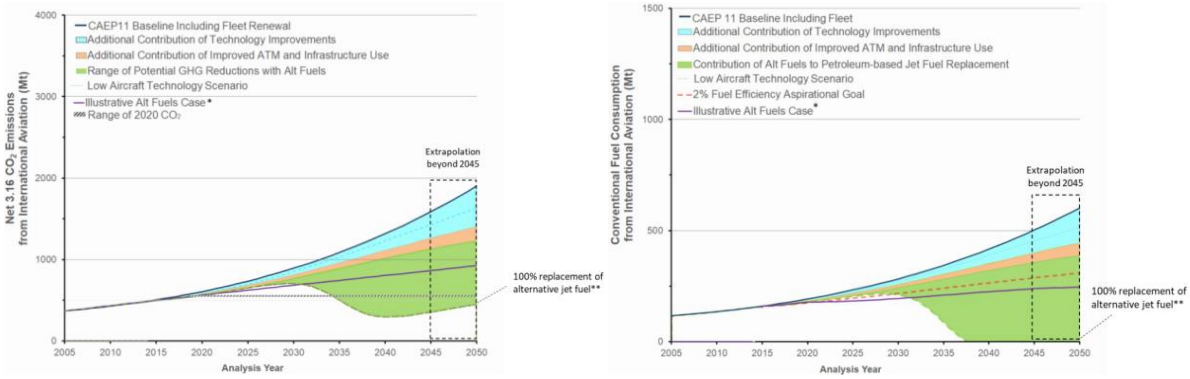


Figure 4.3: Net 3.16 CO_2 Emissions from Aviation, 2005 to 2050: a) International only; b) International plus Domestic [ICAO Environmental Report 2019]

There is a range of uncertainties that contribute to the analysis of the overall trend. The largest by far is the demand uncertainty. See Figures 4.5 for a comparison of demand uncertainty versus other contributions to conventional fuel consumption and net 3.16 CO_2 emissions. Results show that the uncertainty in forecasted demand is rough twice the size of the range in technology and operational improvements combined, which can be considered a proxy to uncertainty in future aircraft technology and operational improvements.

Even under the most optimistic scenario (in Table 4.1 the Fuel 5 scenario), the projected long-term fuel efficiency of 1.37% per annum in CO_2 emissions reduction falls short of ICAO's aspirational goal of 2% per annum. The long-term forecast fuel burn from international aviation is lower by about 25% compared with

prior CAEP trend projections. This decrease can be attributed to a combination of more fuel-efficient aircraft entering the fleet, as well as a reduction in the forecast long-term traffic demand. The computed 1.37% per annum long-term fuel efficiency includes the combined improvements associated with both technology and operations. The individual contributions from technology and operations are 0.98% and 0.39%, respectively. The value 0.98% is slightly lower than the 1.3% cited in the latest CAEP/11 Independent Experts (IE) Review [ICAO, Doc 10127, 2019] for single-aisle aircraft. This indicates that ICAO's aspirational goal of 2% per annum fuel efficiency improvement is unlikely to be met by 2050.



*Illustrative case would require high availability of bioenergy feedstocks, the production of which is significantly incentivized by price or other policy mechanisms; **100% replacement of alternative jet fuel would require a complete shift in aviation from petroleum refining to biofuel production and a substantial expansion of the agricultural sector, both of which would require substantial policy support; Note: Reductions in atmospheric carbon from aviation biofuel use occur from feedstock production and fuel conversion and not from fuel combustion.

Figure 4.4: Net 3.16 CO_2 Emissions from International Aviation, 2005to2050, a) Including Alternative Fuels Life Cycle Emissions Reductions: b) Including Potential Replacement of Jet Fuel with Alternative Fuels [ICAO Environmental Report 2019]

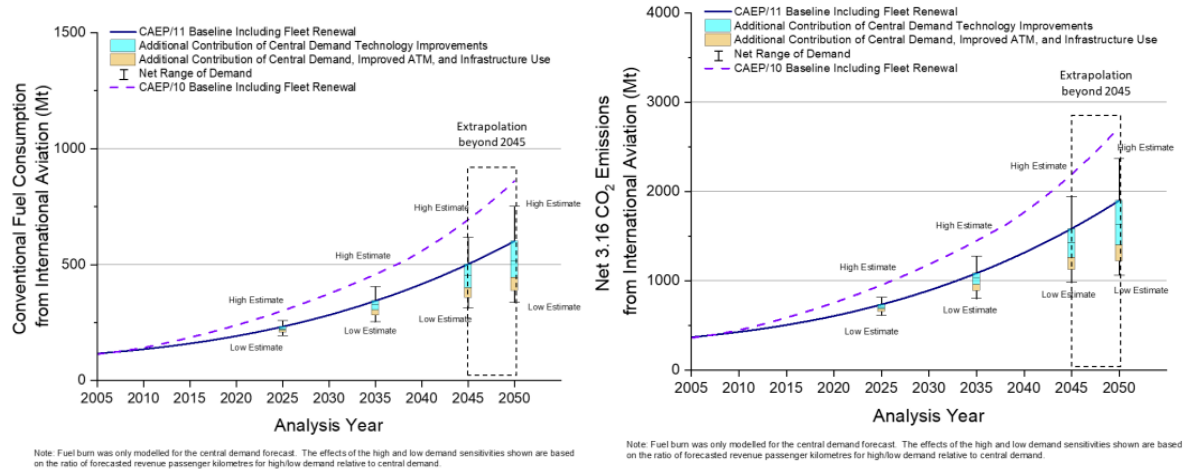


Figure 4.5: Demand Uncertainty versus other Contributions (the CAEP/10 trends baseline is shown for comparison): a) Comparison of Conventional Fuel Consumption from International Aviation, 2005 to 2050; b) Comparison of Net 3.16 CO_2 Emissions from International Aviation, 2005 to 2050 [ICAO Environmental Report 2019]

The demand uncertainty effect on the fuel burn calculations shown in Figure 4.5 has a similar effect on the CO_2 results. With reference to the fuel consumption scenarios in Table 4.1; the highest anticipated fuel consumption in 2020 (Scenario 1), and the lowest anticipated fuel consumption in 2045 (Scenario 5), a minimum CO_2 emission gap of 517 million metric tons (Mt, 1kg × 10^9) is projected for 2045. Extrapolating Scenario 5 to 2050, results in a minimum gap of 612 Mt.

Scenario	Aircraft Technology: per annum fuel burn improvements for fleet entering after base year	Aircraft Technology: Emissions Improvements against CAEP/7 IE NOx Goal	Additional Fleet-Wide OP Improvements by Route Group from Table 2
Fuel 1 - Baseline	NA: use only base-year in-production fleet	NA	NA: maintain baseline meet-demand efficiency
Fuel 2 - Low Aircraft Technology and CAEP/9 IE Operational Improvements	Low: 0.96% to 2015 then 0.57% to 2050	NA	Apply added fleet-wide Table C2 improvements
Fuel 3 - Moderate Aircraft Technology and CAEP/9 IE Operational Improvements	Moderate: 0.96% to 2050	NA	Apply added fleet-wide Table C2 improvements
Fuel 4 - Advanced Aircraft Technology and CAEP/9 IE Operational Improvements	Adanced: 1.16% to 2050	NA	Apply added fleet-wide Table C2 improvements
Fuel 5 - Optimistic Aircraft Technology and CAEP/9 IE Operational Improvements	Optimistic: 1.5% to 2050	NA	Apply added fleet-wide Table C2 improvements
NOx 1 - Baseline	NA	NA	NA
NOx 2 - Moderate Aircraft Technology, CAEP/9 IE Operational, and 50% CAEP/7 IE Emissions Improvements	Moderate: 0.96% to 2050	50% by 2026 nothing thereafter	Apply added fleet-wide Table C2 improvements
NOx 3 - Advanced Aircraft Technology, CAEP/9 IE Operational, and 100% CAEP/7 IE Emissions Improvements	Advanced: 1.16% to 2050	100% by 2026 nothing thereafter	Apply added fleet-wide Table C2 improvements

Table 4.1: CAEP/11 Environment Trends: Fuel and NOx Emissions Scenarios Summary [ICAO Environmental Report 2019]

For 2020, there were six production estimates and two GHG LCA estimates (low and high), resulting in 12 possible GHG emissions scenarios. The 2020 scenarios result in up to 2.6% petroleum-based fuel replacement and up to 1.2% GHG emissions reductions. For 2050, CAEP calculated 60 production achievement scenarios and two GHG emissions scenarios, resulting in a total of 120 scenarios. Certain global conditions, economic investments, and policy decisions are assumed as part of each scenario definition and would be necessary to reach the associated outcome of alternative fuel production and GHG reductions.

Trends in aircraft full flight NOx emissions (Figure 4.6) are based on recommendations from CAEP WG3, NOx scenarios leverage Independent Experts (IE) work from prior CAEP cycles [ICAO CAEP/8-IP/11, 2010], including CAEP/9 assumptions [ICAO CAEP/9 Meeting, 2013] that point to the CAEP/7 IE NOx Goal, which was a 60% improvement from the CAEP/6 NOx Standard plus or minus 5%. See Table 4.1 for additional details on technology, and operational improvement scenarios for NOx. For international aviation, advanced technology and operational improvements could provide additional NOx emission reductions of approximately 2.8 Mt and 0.88 Mt, respectively, in 2050. As with fuel burn, the long-term full-flight NOx from international aviation is lower by about 21% compared with the prior trends projections (Figure 4.6b). This can be attributed to a combination of aircraft with lower NOx engines entering the fleet, as well as a reduction in forecasted long-term traffic demand.

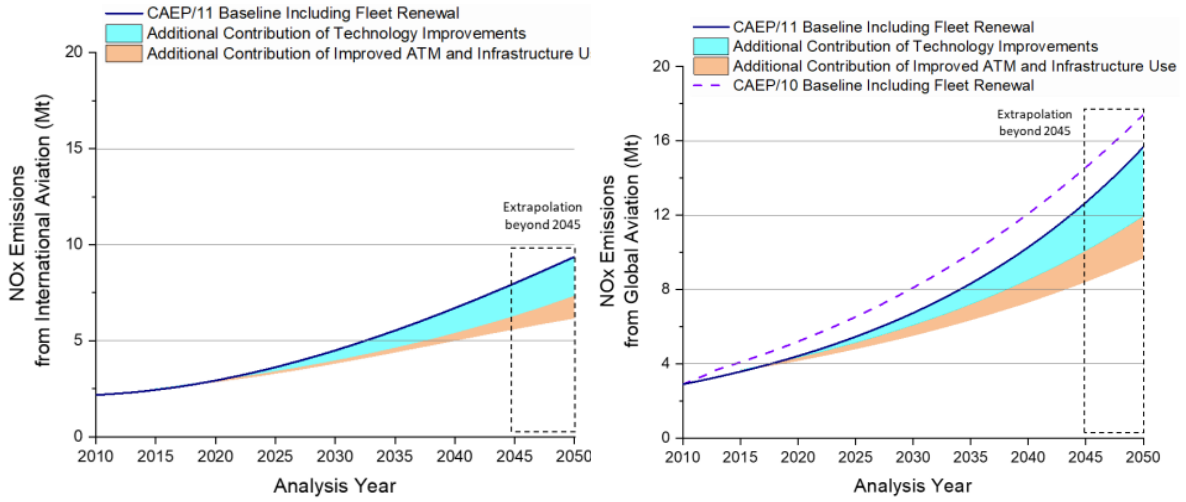


Figure 4.6: NOx Emissions from Aviation, 2010 to 2050: a) International; b) Global (International plus Domestic), with comparison between CAEP/11 and CAEP/10 forecasting [ICAO Environmental Report 2019]

The trend assessment figures for international aviation shown below include the range of CAEP results, and an "illustrative" scenario that achieves 19% net CO_2 emissions reduction, assuming significant policy incentives and high biomass availability. Achieving the most optimistic net CO_2 emissions scenario would require the highest levels of: agricultural productivity, availability of land for feedstock cultivation, residue removal rates, conversion efficiency improvements, and reductions in the GHG emissions of utilities. It would also require a strong market or policy emphasis on bioenergy in general, and alternative aviation fuel in particular.

Achievement of carbon-neutral growth at 2020 emissions levels out to 2050 would require nearly complete replacement of petroleum-based jet fuel with sustainable alternative jet fuel and the implementation of aggressive technological and operational scenarios. The effort required to reach these SAF production volumes would have to significantly exceed historical precedent for other alternative fuels, such as ethanol and biodiesel for road transportation. This analysis [ICAO Environmental Report 2019] also considered the long-term availability of SAF, finding that it would be physically possible to meet 100% of demand by 2050 with SAF, corresponding to a 63% reduction in emissions. However, this level of fuel production could only be achieved with extremely large capital investments in sustainable alternative fuel production infrastructure and substantial policy support.

A range of scenarios was developed for the assessment of future noise trends [ICAO Environmental Report 2019]. The noise indicators used are the total contour area and population inside the yearly average day-night level (DNL) 55 dB contours of 315 airports worldwide, representing approximately 80% of the global traffic. Aircraft noise was modelled for 4 scenarios (baseline and low, moderate, and advanced technology). The technology improvement scenarios used for the noise trends assessment are given in Table 4.2, with detailed descriptions below, including those related to operational improvements. Scenario 1 (CAEP/11 Baseline) assumes no further aircraft technology or operational improvements after 2015. Scenarios 2, 3, and 4 (low, moderate, advanced technology) assume that the noise levels of all new aircraft delivered after 2015 will reduce at a rate of 0.1, 0.2, and 0.3 EPNdB 4 per annum, respectively. For all scenarios, an additional 2% reduction is applied to the population counts inside the noise contours, to reflect a possible improvement of aircraft routing around airports.

	Baseline Scenario	Technology Improvements Scenarios		
Analysis Year	No New Technology (scenario 1)	Low (scenario 2)	Moderate (scenario 3)	Advanced (scenario 4)
2015	X	Not Applicable		
2025	X	X	X	X
2035	X	X	X	X
2045	X	X	X	X

Table 4.2: Scope of CAEP/11 Noise Trends Assessment

Figure 4.7a shows the total 55 dB DNL noise contour area from 2010 to 2050. In 2015, this area was 14,400 square-kilometres, and the population inside that area was approximately 30 million people. By 2045, the area is expected to grow from 1.0 to 2.2 times, compared with 2015, depending on the technology scenario. Of note is that under the advanced aircraft technology scenario (Scenario 4), from about 2030 onwards, the total yearly average DNL contour area may no longer increase with an increase in traffic. The long-term total DNL 55 dB contour area is lower by about 10%, compared with the prior trends projections. This decrease can be attributed to a combination of quieter aircraft entering the fleet, as well as a reduction in the long-term traffic demand.

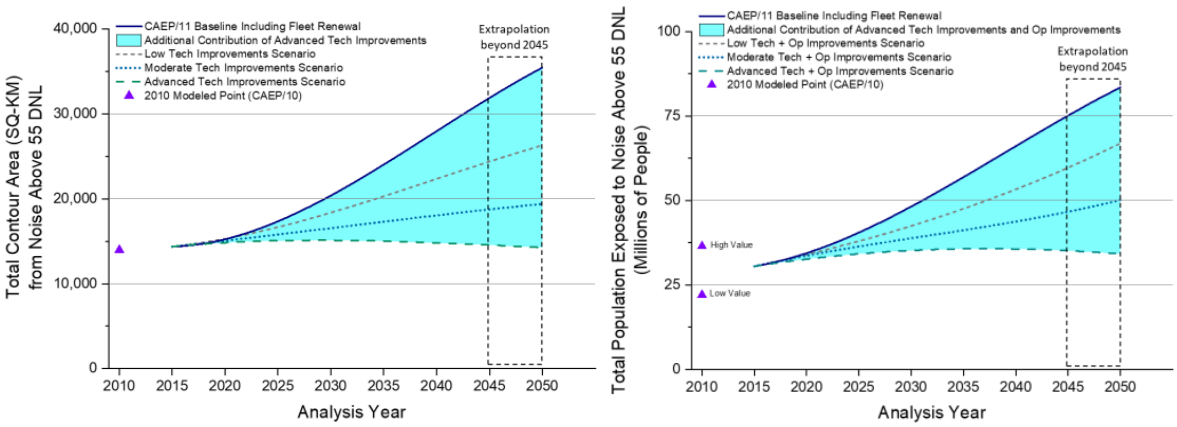


Figure 4.7: Total Aircraft Noise exposure assessment for 315 Airports, 2010 to 2050: a) Contour Area Above 55 dB DNL (km^2); b) Global Population Exposed to Noise Above 55 DNL

Figure 4.7b provides results for the total global population exposed to aircraft noise above 55 DNL for 2015, 2025, 2035 and 2045 for the four scenarios. Historical data modelled in the CAEP/10 work cycle is also shown for 2010, with a range in population values since multiple population databases were used. The 2015 baseline value is 30.5 million people. In 2050, the total population exposed increases to 34.2 million people with the advanced technology and operational improvement scenario, and to 66.9 million people with low technology and operational improvement scenario.

A range of scenarios have also been developed for the assessment of aircraft emissions that occur below 3,000 feet above ground level (AGL) and affect local air quality: namely NOx and total (volatile and non-volatile) particulate matter (PM). The NOx scenarios are the same as in Table 4.1. For assessing PM trends, there are two scenarios as follows: Scenario 1 (CAEP/11 Baseline) assumes no further aircraft technology or operational improvement after 2015. Scenario 2, represented by the bottom of the orange sliver, assumes that only operational improvements apply, with no aircraft technology improvements. Figure 4.8 provides results for NOx emissions below 3,000 feet AGL from international aviation from 2010 to 2050. The 2015 NOx emissions were 0.18 Mt. In 2045, they are forecast to range from 0.44 Mt under Scenario 3, to 0.80 Mt under Scenario 1.

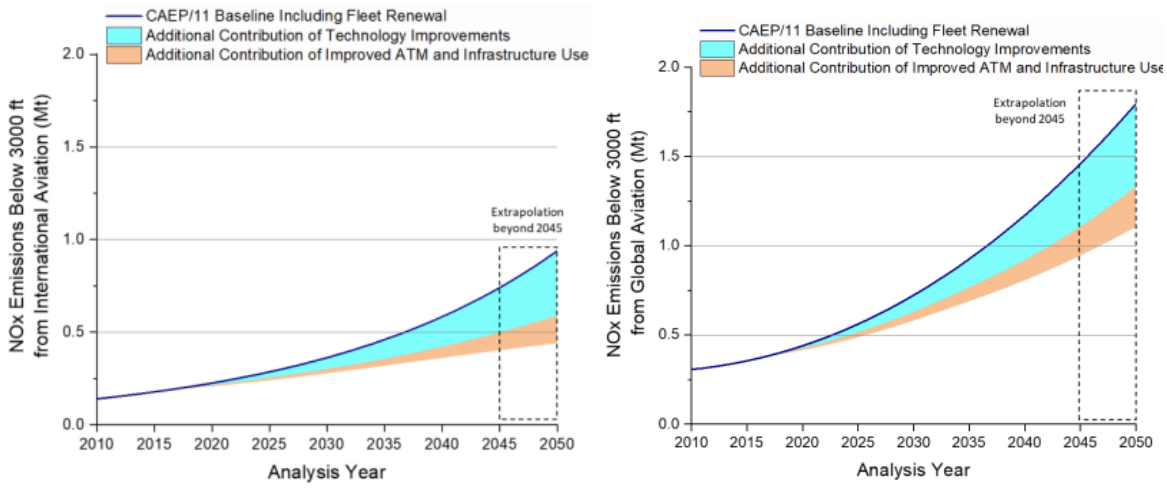


Figure 4.8: NOx Emissions below 3000 ft from Aviation, 2010 to 2050: a) International; b) International plus Domestic

The projections of global NOx emissions below 3,000 feet are lower by about 2% compared with the prior trend projections. This will be due to three main factors: a combination of aircraft with lower NOx engines, a reduction in the long-term traffic demand, and a refinement to the method used for computing emissions below 3,000 feet. Operational improvements are smaller than those that could be realized by technology, namely additional reductions of up to 0.15 and 0.23 Mt in 2050 for international and global aviation, respectively.

The results for PM emissions from international aviation below 3,000 feet AGL follow similar trends as those for NOx, as shown in Figure 4.9. The 2015 PM emissions were 1,243 tons (t). In 2045, they are projected to range from 3,230 t under Scenario 2, and 3,572 t under Scenario 1. Operational improvements could provide additional reductions of up to 1160 tonnes and 3100 tonnes in PM emissions in 2050 for international and global aviation, respectively.

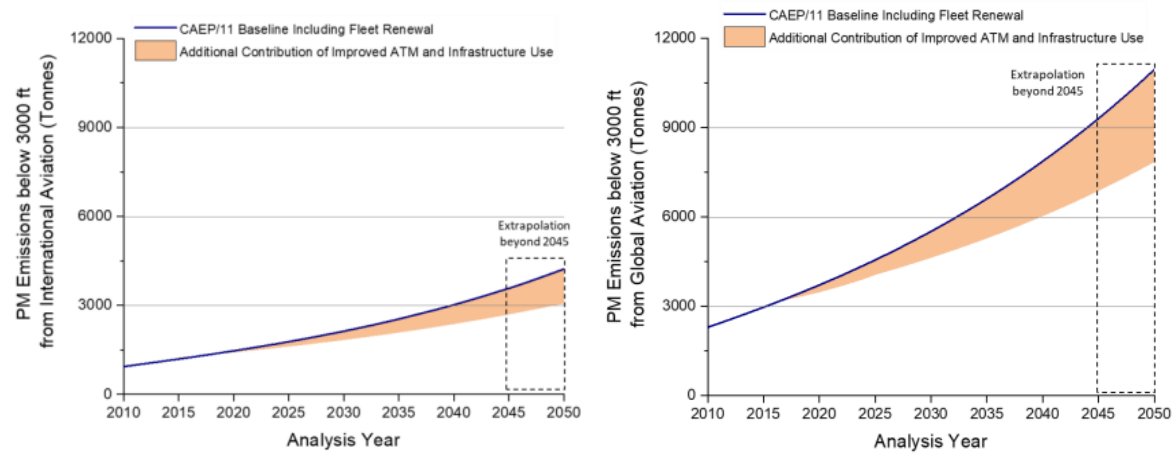


Figure 4.9: PM Emissions below 3000 ft from Aviation, 2010 to 2050: a) International; b) International plus Domestic

Emissions from international aviation that affect the global climate and local air quality are expected to increase through 2050, by a factor ranging from approximately 2 to 4 times the 2015 levels, depending on the type of emissions(CO_2, NOx or PM), and the analysis Scenario used. Under an advanced aircraft technology scenario, the total area of day-night levels (DNL) noise contours around airports may stabilize after 2030. However, it should be kept in mind that the uncertainty associated with future aviation demand is notably larger than the range of contributions from technology and operational improvements.

The Environmental Noise Directive (END) [EC, 2002, Directive 2002/49/EC] and Balanced Approach Regulation [EC, 1996, Future noise policy; EEA, 2014, Noise in Europe; EEA, 2010, Good practice guide; EU, 2014, Regulation (EU) 598/2014] are the overarching EU legislative instruments under which environmental noise is monitored, communicated to the public and actions are taken. Member States are applying common criteria for noise mapping as well as developing and implementing local policies and action plans to reduce noise exposure in large cities and in the vicinity of major transport infrastructure.

In comparison with ICAO CAEP global trend assessments in EU (EU28+European Free Trade Association - EFTA) airports is expected to reach 13.6 million in 2040, compared to 9.6 million in 2017 (Figure 4.10a) under the most-likely future scenario. Current growth is certainly supported by strong demand. This growth has brought traffic back to the most-likely scenario from the 2013 forecast (Figure 4.10b). This represents an average annual growth rate of 1.5% over this period. Although the forecast has been updated since the previous report, actual traffic growth has followed the base forecast, which explains why the 2035 figure remains unchanged. The total population residing inside the L_{den} 55 dB and L_{night} 50 dB contours of the 47 major European airports were 2.58 and 0.98 million people respectively in 2017 (Figure 4.11, Table 4.2). This is 12% and 13% more than in 2005 for L_{den} and L_{night} respectively, but 14% and 20% more than in 2014. However, some airports within the 47 have seen their L_{den} and L_{night} contours reduced. The total noise energy in the EU28 and EFTA region follows flight counts closely (Figure 4.12) but was 5% lower in 2017 than in 2005, indicating that noise technology has managed to compensate for the increase in average aircraft size. The average noise energy per flight indeed went down by 14% over this period. Figure 4.12 presents the relative evolution of key air traffic and environmental indicators since 2005. This shows an increase in economic and connectivity benefits from aviation (measured in passenger-kilometres flown) with a lower rate of increase in environmental impacts.

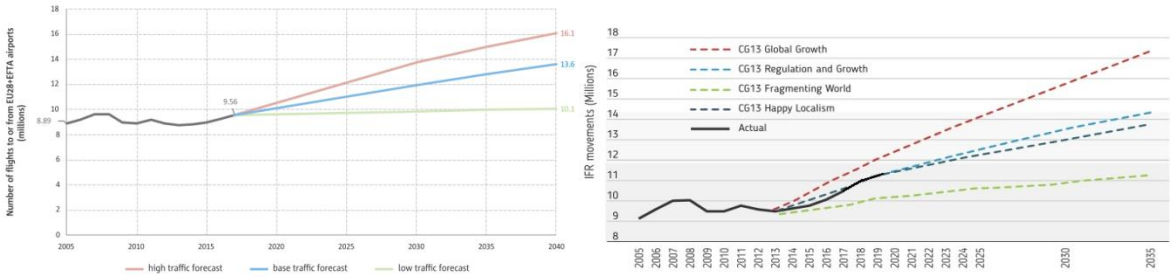


Figure 4.10: Number of flights increases by 42% between 2017 and 2040 under the base traffic forecast: a) forecasting from [EASA, EEA, EUROCONTROL, 2019]; b) forecasting from [European Aviation in 2040, 2018]

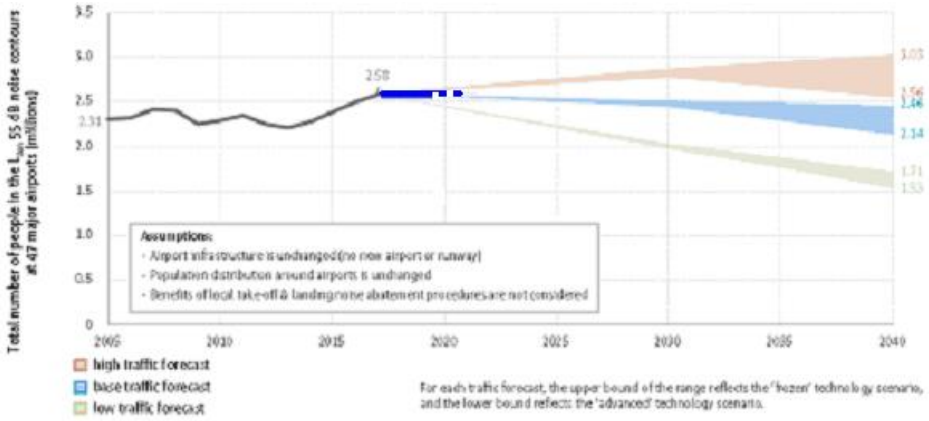


Figure 4.11: Fleet renewal could stabilize average noise levels at today's 47 major airports by 2030 [EASA, EEA, EUROCONTROL, 2019]

If the latest aircraft types now entering the fleet deliver their expected noise benefits, the total population exposed to L_{den} 55 dB and L_{night} 50 dB noise levels around the 47 major airports could stabilize even for the scenario of Global Growth (most optimistic) and even start to decrease by 2030 (in comparison with

continuous increase globally, Figure 4.7). This forecast assumes that there will be no further airport expansion and no change in population around these airports. Furthermore, around 110 airports could handle more than 50,000 annual aircraft movements by 2040, compared to 82 airports in 2017, thereby affecting new populations. Taking in mind the current trend – close to Regulation and Growth scenario – a total number of exposed to AN population should stabilize in Europe much earlier, it is expected at the beginning of 2020s.

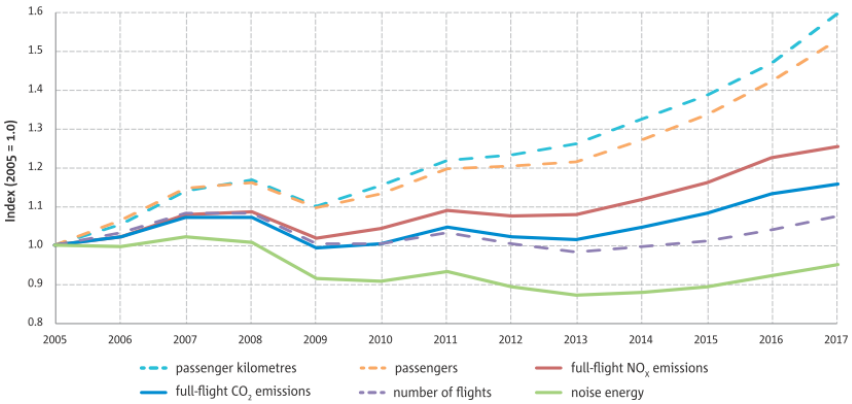


Figure 4.12: Noise and emissions grow slower than passenger kilometres but emissions grow faster than number of flights [EASA, EEA, EUROCONTROL, 2019]

In 2010, EU and EFTA States agreed to work through the ICAO to achieve a global annual average fuel efficiency improvement of 2% and to cap the global net carbon emissions of international aviation at 2020 levels. During 2012, Member States submitted Action Plans to the ICAO for the first time, outlining their respective policies and actions to limit or reduce the impact of aviation on the global climate. Updated and extended State action plans were subsequently provided in 2015 and 2018.

The EU plays a leading role in international efforts to limit climate change and increased its climate finance contributions to €20.2 billion in 2016. This is backed up by a legally binding commitment and legal framework at EU level to reduce greenhouse gas emissions, increase the use of renewable energy and improve energy efficiency [EU, 2018, European Semester; EEA, 2017, Trends; EU, 2018, EU climate and energy framework; EC, 2011, White Paper]. These 'climate and energy' targets for 2020, which the EU is on track to meet, and 2030 are summarized below:

2020

- 20% cut in greenhouse gas emission (from 1990 levels);
- 20% of EU energy from renewable;
- 20% improvement in energy efficiency;

2030

- At least 40% cut in greenhouse gas emission (from 1990 levels);
- 32% of EU energy from renewables, with an upwards revision clause by 2023;
- 32.5% improvement in energy efficiency, with an upwards revision clause by 2023.

The EU has also agreed on a "*2050 low carbon economy*" roadmap that suggests the following targets:

- 60% cut in greenhouse gas emission by **2040** (from 1990 levels);
- 80% cut in greenhouse gas emission by **2050** (from 1990 levels), including a 60% reduction in transport emissions.

At the request of the European Council and the European Parliament, the EC presented its vision for long-term EU GHG emissions reductions in accordance with the Paris Agreement in November 2018, showing that decarburization is possible by 2050, including aviation. The goal agreed under the Paris Agreement is to limit the global temperature increase to well below 2 degrees Celsius compared to pre-industrial levels, while

pursuing efforts to limit the increase to 1.5 degrees. While this covers all man-made emissions, including aviation, measures to reduce these emissions are covered by the Nationally Determined Contributions under the Paris Agreement as well as global measures developed through the relevant international organizations, such as ICAO. From an aviation perspective, the EU has invested approximately €5 billion over the last 10 years to support these commitments through various programs (e.g. Clean Sky, SESAR, Life, Horizon 2020, Connecting Europe Facility) and a basket of measures (e.g. EU ETS, CORSIA, aeroplane CO_2 certification standard) that are summarized in the chapters of the report [EASA, EEA, EUROCONTROL, 2019].

In 2016, aviation was accountable for 3.6% of the total EU28 greenhouse gas emissions and for 13.4% of the emissions from transport, making aviation the second most important source of transport GHG emissions after road traffic [EEA, 2018, Greenhouse gas]. Greenhouse gas emissions from aviation in the EU have more than doubled since 1990, when it accounted for 1.4% of total emissions. As emissions from non-transport sources decline, the emissions from aviation become increasingly significant [EEA, 2017, Trends]. European aviation represented 20% of global aviation's CO_2 emissions in 2015.

According to the data reported by Members States to the United Nations Framework Convention on Climate Change (UNFCCC), the CO_2 emissions of all flights departing from EU28 and EFTA increased from 88 to 171 million tons (+95%) between 1990 and 2016 (Figure 4.13). In comparison, CO_2 emissions estimated with the IMPACT model reached 163 million tons (Mt) in 2017, which is 16% more than in 2005 and 10% more than in 2014. Over the same period, the average fuel burn per passenger-kilometre flown for passenger aircraft, excluding business aviation, went down by 24%. This has reduced at an average rate of 2.8% per annum between 2014 and 2017.

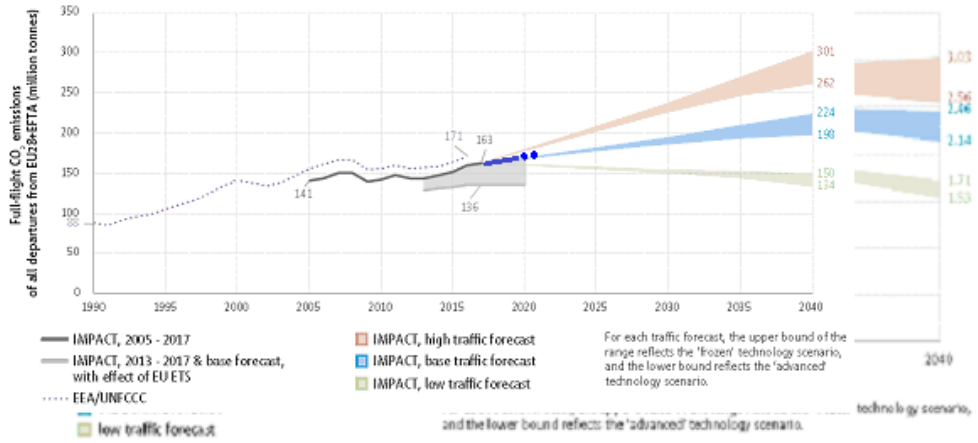


Figure 4.13: CO_2 emissions are steadily increasing again since 2013 [EASA, EEA, EUROCONTROL, 2019]

However, this efficiency gain was not sufficient to counterbalance the increase in CO_2 emitted due to the growth in the number of flights, aircraft size and flown distance. Future CO_2 emissions under the base traffic forecast and advanced technology scenario (close to Regulation and Growth scenario in Figure 4.10) are expected to increase by a further 21% to reach 198 Mt in 2040 (blue area in Figure 4.13). The annual purchase of allowances by aircraft operators under the EU Emissions Trading System (ETS) since 2013 resulted in a reduction of 27 Mt of net CO_2emissions in 2017, which should rise to about 32 Mt by 2020.

The use of sustainable aviation fuel in European Aviation sector is currently minimal and is likely to remain limited in the short term. SAFs have the potential to make an important contribution to mitigating the current and expected future environmental impacts of aviation. Regular flights using blends of bio-based aviation fuel are already being performed from several airports in the EU, albeit at very low percentages of the total fuel uplift. The EU has the potential to increase its bio-based aviation fuel production capacity, but the uptake by airlines remains limited due to various factors, including the cost relative to conventional aviation fuel and low priority in most national bioenergy policies. Recent policy developments and industry initiatives aim to

have a positive impact on the uptake of sustainable aviation fuels in Europe [EASA, EEA, EUROCONTROL, 2019].

EU air pollution legislation follows a twin-track approach of implementing both local air quality standards [EEA, 2017, Air quality in Europe; EEA, 2018, Greenhouse gas] and source-based mitigation controls (e.g. engine emissions and fuel quality standards). Binding national limits for emissions of the most important pollutants have also been established in the EU, but not all aviation activities are included [EU, 2016, EU Directive 2016/2284]. Aviation is also an important source of air pollutants, especially of NOx and PM. In 2015, it accounted for 14% of all EU transport NOx emissions, and for 7% of the total EU NOx emissions. In absolute terms, NOx emissions from aviation have doubled since 1990, and their relative share has quadrupled, as other economic sectors have achieved significant reductions. The CO and SOx emissions from aviation have also gone up since 1990, while these emissions from most other transport modes have fallen [EEA, TERM 2017].

NOx emissions have followed a steeper upwards trend than CO_2 in recent years (Figure 4.14). They increased from 313 to 700 thousand tons between 1990 and 2016 according to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) data from the UN Economic Commission for Europe, and by 25% between 2005 and 2017 according to estimates from the IMPACT model.

Unlike the CO_2 trend, current predictions indicate that the advanced engine NOx technology scenario could lead to a downward trend after 2030. However, NOx emissions would still reach around 1 million tons in 2040 under the base traffic forecast (blue area in Figure 4.14) or+45% compared to 2005.

The COVID-19 pandemic has had a significant impact on the aviation industry due to the resulting travel restrictions as well as slump in demand among travellers [https://en.wikipedia.org/wiki/Impact_of_the_COVID-19_pandemic_on_aviation]. In response to the Covid-19 pandemic, air traffic has slumped in a manner not seen since the aftermath of the 9/11 attacks on the United States in 2001. Significant reductions in passenger numbers have resulted in planes flying empty between airports and the cancellation of flights. Early March 2020 saw 10% of all flights cancelled, compared to 2019. As the pandemic progressed, 40-60% lower number of flight movements were recorded in late March with international flights affected the most. By April over 80% flight movements were restricted across all geographies, including North America, Europe and Asia and all sectors. Global demand for air travel is down 70% compared to last year and millions of jobs are at risk, according to the IATA, which represents airlines.

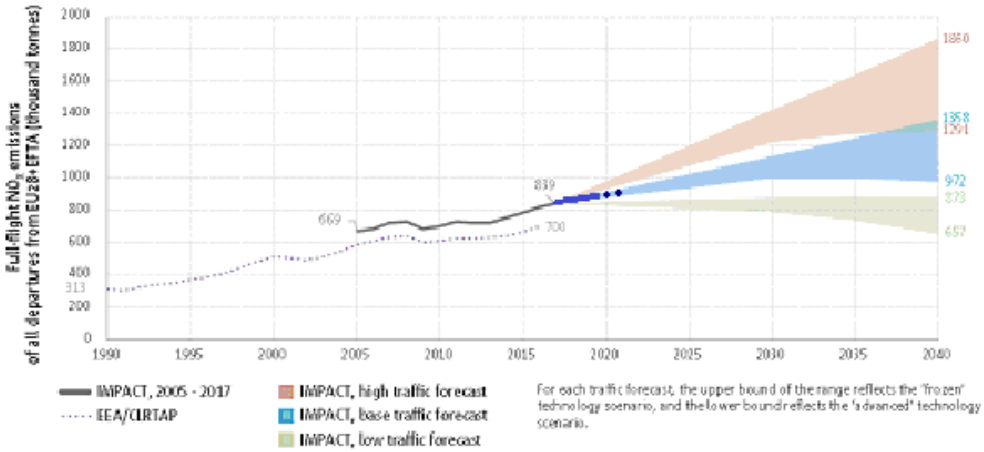


Figure 4.14: NOx emissions will increase further, but advanced engine combustor technology could help curb their growth after 2030 [EASA, EEA, EUROCONTROL, 2019]

Understanding planes' impact on the climate is urgent because commercial aviation generates about 2% of global carbon emissions and rising, mainly from burning jet fuel. Taking into account the impact of cloud formation in the upper atmosphere, however, could make the sector's responsibility for human-caused

global warming as high as 4% or 5%. "It is welcome that we can have an experiment with the Earth," said Ulrike Burkhardt, of the Institute of Atmospheric Physics at the German Aerospace Center (DLR) [Doyle A., 2020]. "But it's not the way we would want to design it."Researchers will use satellites and measurements by planes to study how clouds form naturally when thousands of flights are grounded and contrast it with data from pre-coronavirus conditions of crowded skies. In the long term, that could help governments set better policies.

"The air traffic system has not been diminished to the current levels since the days following 9/11," said Patrick Minnis of NASA Langley Research Center, who is joining a research effort to study high-altitude clouds [Doyle A., 2020]. "Flight groundings at the scales initiated in response to the coronavirus pandemic are a significant opportunity to better quantify the impact of air traffic on cloud cover via contrail formation."Minnis and colleagues are trying to determine whether contrails increase the total amount of clouds in the sky, or suck up moisture that might have allowed clouds to form elsewhere. That would help to establish whether contrails and cloudiness linked to aviation had an overall warming or cooling effect on the planet.

Piers Forster, Professor of Physical Climate Change at the University of Leeds, said that the "total historic warming from aviation is roughly twice that from its carbon dioxide emissions alone" [Doyle A., 2020]. "The total warming effect of aviation is still small: maybe 5% of the warming from all human activity," Forster said, factoring in cloud formation. "But as other emissions will hopefully decline, it is expected that aviation will be the dominant source of emissions within the next few decades…

When assessing the economic impacts on civil aviation, ICAO works with many different scenarios [https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx] in order to reflect the very uncertain nature of the current situation and the rapidly changing environment. In order to explore the potential economic implication of the COVID-19 pandemic for the near future (Figure 4.15), the full report is built around 6 different recovery paths under two indicative scenarios.

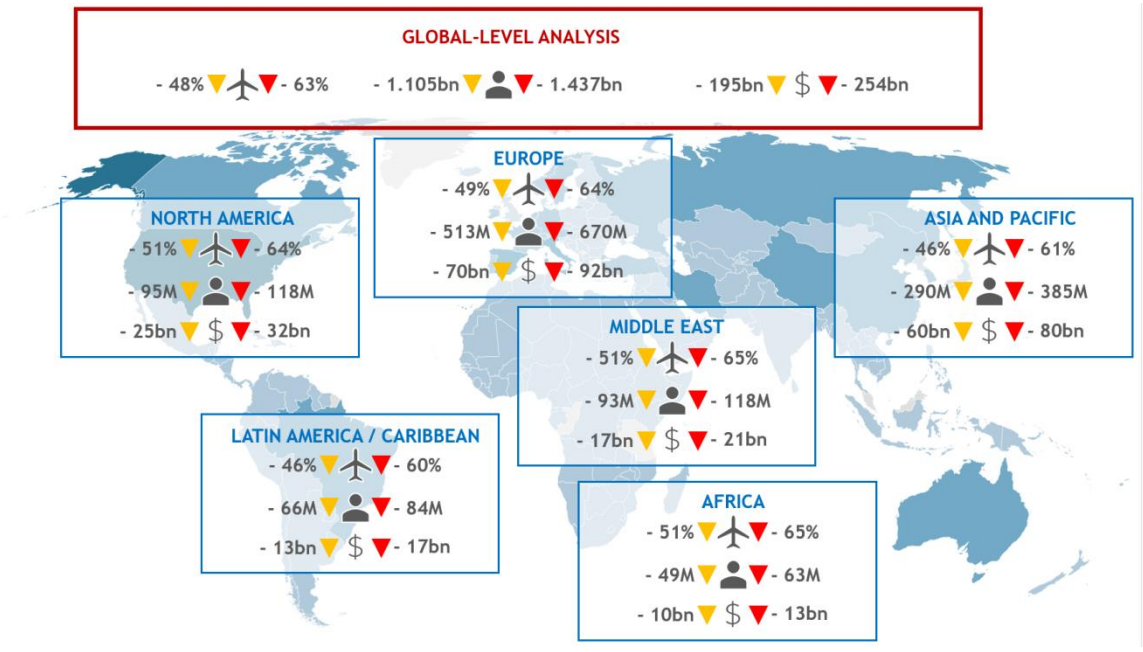


Figure 4.15: Global-level Analysis [https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx] (The data are valid to 25 of July 2020)

The actual path will eventually depend upon various factors, inter alia, duration and magnitude of the outbreak and containment measures, availability of government assistance, consumers' confidence and economic condition:

1. **Baseline :** hypothetical situation without COVID-19 outbreak with forecasts as originally planned;
2. **Indicative Scenario 1 - "V-Shaped":** follows the normal shape for recession where a brief period of contraction is followed by quick/smooth recovery - most optimistic path indicated with a ▼;
3. **Indicative Scenario 2 - "U-Shaped":** indicates prolonged contraction and muted recovery with a possibility of no return to trend line of growth (L-shaped) - most pessimistic path indicated with a ▼;

The analytical focus, in the report [https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx], is on the near-term with monthly profiles from Jan to Dec 2020 and on international traffic only. Scenarios 1 and 2 are not forecasts of what is likely to happen, but merely indicators of possible paths or consequential outcomes out of many. Each scenario considers 3 different paths to take into account differentiated terms of supply (output) and demand (spending).

The latest estimates indicate that the possible COVID-19 impact on scheduled international passenger traffic for the full year 2020, compared to Baseline (counterfactual scenario, in which the COVID-19 pandemic does not occur, so trend line growth from 2019 level, that is, originally-planned or business as usual, Figure 4.16, 4.17), would be:

Scenario 1: V-shaped path (normal shape for a recession, a brief period of contraction followed by quick/smooth recovery a first sign of recovery in late May):

- Overall reduction ranging from 38% to 55% of seats offered by airlines;
- Overall reduction of 861 to 1,292 million passengers;
- Approx. USD 151 to 228 billion potential loss of gross operating revenues of airlines.

Scenario 2: U-shaped path (prolonged contraction and muted recovery, possibility of not to return to trend line growth (L-shaped) bottom out and pick up in third quarter or later):

- Overall reduction ranging from 48% to 71% of seats offered by airlines;
- Overall reduction of 1,108 to 1,524 million passengers;
- Approx. USD 194 to 269 billion potential loss of gross operating revenues of airlines.

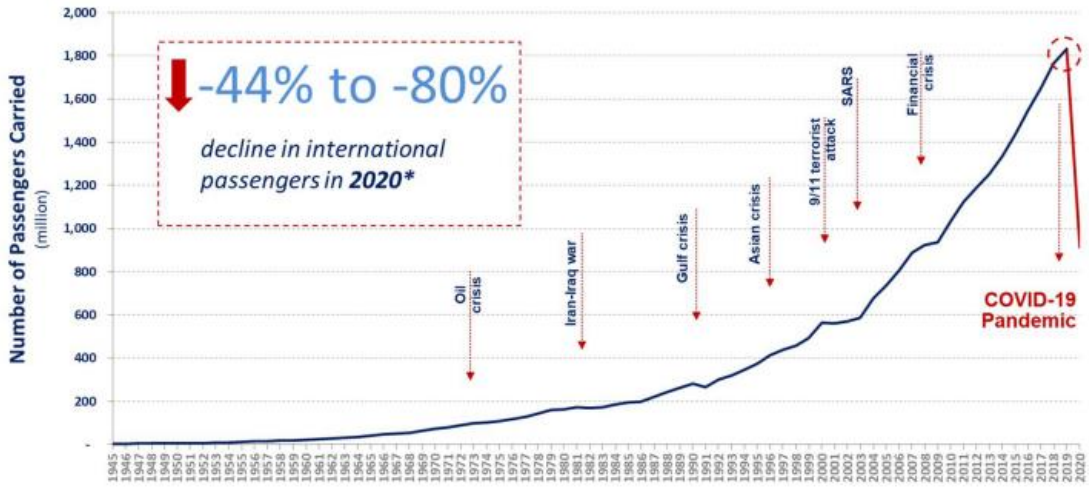


Figure 4.16: World international passenger traffic evolution 1945 – 2020[https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx]

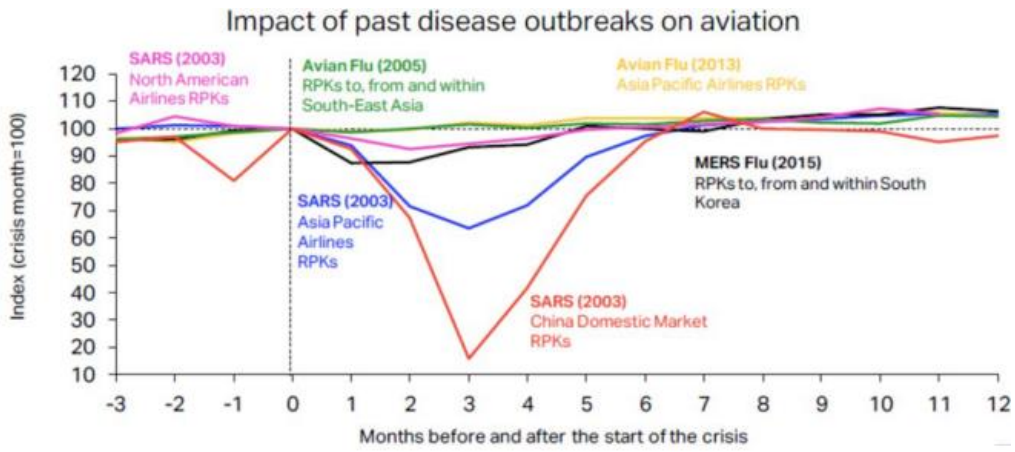


Figure 4.17: V-shaped and U-shaped paths [https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx]

The impacts depend on the duration and magnitude of the outbreak and containment measures, the degree of consumer confidence for air travel, and economic conditions (Figure 4.18), etc. Analytical focus, for the time being, on:

- Near-term, i.e. monthly profile from January to December 2020;
- Scheduled international passenger traffic*.

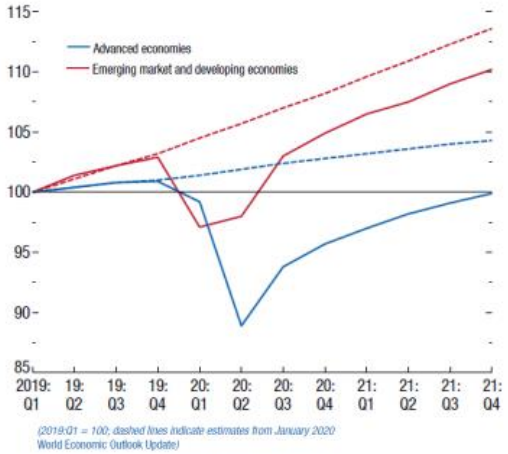


Figure 4.18: World's GDP Projections (by IMF) [https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020]

Global impact of COVID-19 on aviation, tourism, trade and economy:

- *International air passenger traffic*: An overall reduction of international passengers ranging from 44% to 80% in 2020 compared to 2019 (by ICAO);
- *Airports*: An estimated loss of over 50% of passenger traffic and 57% or over USD97 billion airport revenues in 2020 compared to business as usual (by ACI);
- *Airlines*: A 48% decline of revenue passenger*kms (RPKs, both international and domestic) in 2020 compared to 2019 (by IATA);
- *Tourism*: Decline in international tourism receipts of between USD 910 to 1,170 billion in 2020,compared to the USD 1.5 trillion generated in 2019, with 96% of worldwide destinations having travel restrictions (by UNWTO);
- Trade: A fall of global merchandise trade volume by between 13 and 32% in 2020 compared to 2019 (by WTO);

- Global economy: A projected -3% contraction in world GDP in2020, far worse than during the 2008–09 financial crisis (by IMF).

Scenarios 1 and 2 are not forecasts of what is most likely to happen. Given a rapidly changing environment, these scenarios are merely indicative of possible paths or consequential outcomes out of many. The exact p ath (depth, length and shape) will depend upon various factors, inter alia, duration and magnitude of the ou tbreak and containment measures, availability of government assistance consumer confidence, and econo mic conditions.

Scenarios 1 and 2 are differentiated in terms of supply (output) and demand (spending) conditions, mainly, a) the timing and scale of airline capacity decline and recovery, and b) the degree of consumer confidence in air travel that can be translated into demand or load factor. The impact of COVID-19 has already surpassed the 2003 SARS outbreak which had resulted in a reduction of annual RPKs by 8% and USD 6 billion revenues for Asia/Pacific airlines. The 6-month recovery path of SARS might not apply to today's situation (Figure 4.19).

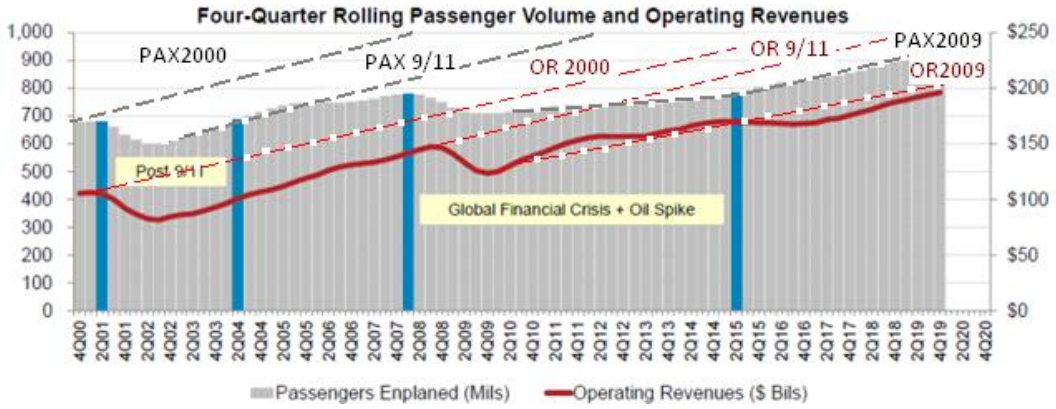


Figure 4.19: 9/11 and global financial crisis had a U/L-shaped impact on air transport in United States

Due to extreme uncertainty, 6 different paths up till 4Q 2020 are considered:

- Baseline (counterfactual, no COVID-19 pandemic):
  - Originally-planned or business as usual: trend line growth from 2019 level
- Scenario 1 (V-shaped path, a first sign of recovery in late May):
  - Path 1: Gradual capacity recovery to 80% of Baseline level by December but weak demand return;
  - Path 1a: Swift capacity rebound to 90% pushed by pent-up demand;
  - Path 1b: Slow progression to recover 60% capacity with downside risk in demand;
- Scenario 2 (U-shaped path, bottom out and pick up in 3/4Q or even later):
  - Path 2: Slow progression of capacity recovery to 50% of Baseline with sluggish demand growth;
  - Path 2a: Swift capacity rebound to 90% by December, outpacing demand recovery;
  - Path 2b: Prolonged downturn towards 2021 with marginal seasonal adjustments.

The impact of COVID-19 is still under the development, its recovery path is not understanding completely to today's situation. In the further text of Chapter 4, COVID-19 impact is not considered.

The degree of change makes the future more uncertain but it also makes the technology program and timing described in this section key if results are to be achieved by 2050. It is also essential that this technology roadmap and its implementation continue to receive support through government policy and that it remains a priority for European society (Table 4.3).

No	Action area	2050 target state	Impact
3.1	Develop air vehicles of the future: evolutionary steps	These actions result in evolutionary aircraft developments that have driven progress in environmental performance towards FP2050 goals. Changes are introduced both into new aircraft and by retrofit across the civil aerospace fleet.	Research and innovation for evolutionary aircraft development described in this action area will drive progress in environmental performance to be on track towards the FP2050 goals. Changes will be introduced in new aircraft or by retrofit into the growing civil aerospace fleet.
3.2	Develop air vehicles of the future: revolutionary steps	New technologies have been developed and implemented that significantly surpass the capabilities of earlier-generation aircraft whilst improving on the high levels of reliability, safety and usability that customers demand.	New technologies will significantly surpass the capabilities of today's aircraft whilst maintaining or improving on the high levels of reliability, safety and usability that customers demand.
3.3	Increase resource use efficiency and recycling	Resources, materials and new processes are better focused on providing a sustainable aviation sector. End-of-service is characterized by high recyclability and reuse.	The proposed actions will ensure the development of sustainable aeronautical products through increased recyclability and reuse at the end of service life to ensure better use of resources, materials and processes.
3.4	Improve the environmental performance of air operations and traffic management	New operational practices are implemented resulting in optimised trajectories and reduced fuel-burn per flight in accordance with FP2050 goals. The FP2050 goal of emission-free taxiing is well on the way to being realized.	The operational gains resulting from these research activities will induce a reduction of between 250kg and 500kg of fuel (800kg to 1600kg of CO_2) per flight - 5-10% of the total - as a major contribution towards the Flightpath 2050 goal of a 75% reduction. This includes a 30% reduction in taxiing fuel-burn per flight due to advanced taxiing operations in pursuit of the goal of emission-free taxiing.
3.5	Improve the airport environment	Air quality is improved and noise annoyance is reduced to acceptable levels. Airports are fully integrated and accepted by local communities. Intermodal transport connections are efficient and environmentally friendly.	Specific research for the airport environment will permit significant improvement in air quality and reduction of noise annoyance at European airports, with the most appropriate solutions for these key environmental concerns.
3.6	Provide the necessary quantity of affordable alternative energy	Sustainable alternative fuels are widely used contributing to a substantial reduction in aviation's impact on climate change. Disruptive alternatives for energy storage and supply are increasingly viable.	Research and technology results on alternative aviation fuels, in cooperation with the renewable sector and backed by a favourable policy framework, will enable the large-scale deployment of sustainable alternative fuels, which will contribute to a substantial reduction of aviation's climate impact.
3.7	Understand aviation's climate impact	There is a detailed, scientific understanding of the impact of aviation on the climate. This has enabled the introduction of sound, globally harmonized policies and regulations to support climate-friendly flight operations.	Improvements in scientific understanding of aviation climate impact will enable the introduction of scientifically-founded and globally-harmonized policy and regulations to support climate-friendly flight operations, and will highlight the mitigation priorities for manufacturers.
3.8	Adapt to climate change	Impacts of climate change on aviation are well understood and steps have been taken to protect the efficient	The understanding of climate change risks to aviation, and implementation of measures to tackle them, are essential to facilitate safe

		operations of air transport and the integrity of its infrastructures.	and efficient operation of air transport and to protect its infrastructure in the face of increasing impacts.
3.9	Develop incentives and regulations	There exists a comprehensive framework of policy, regulation and incentive to ensure the implementation of new technologies and operations destined to reduce the impact of aviation on climate change.	The implementation of new technologies to reduce the environmental impact of aviation, including a transition to more renewable energies, will only work if embedded in a holistic transport and energy policy framework. Research in this field will deliver these incentives and regulations to support the FP2050 goals.

Table 4.3: The action areas for *Challenge 3* of the ACARE perspectives, transformed from [Strategic Research and Innovation Agenda, 2017]

In recent years the aviation sector has initiated a comprehensive range of measures to mitigate its GHG emissions. To achieve the 2050 goals, step changes in aircraft configuration and operation (including alternative energy sources) will be required (Figure 4.20) – currently envisaged evolutions will not be sufficient [Strategic Research and Innovation Agenda, 2017], there is a need a real basket of measures! Such disruptive change will have consequences for all stakeholders: manufacturers, airlines, airports, ANSPs and energy suppliers. ACARE runs three research projects to achieve these goals: X-Noise EV, which relates to aviation noise research, Forum AE, which relates to emissions research, and Core-Jet Fuel, which relates to alternative aviation fuels. A 1st decade of the Roadmap to vision 2050 is covered. Mid-term achievements may be done, so as some corrections to long-term goals, which are quite different between ICAO, EU and other world (Table 4.4).

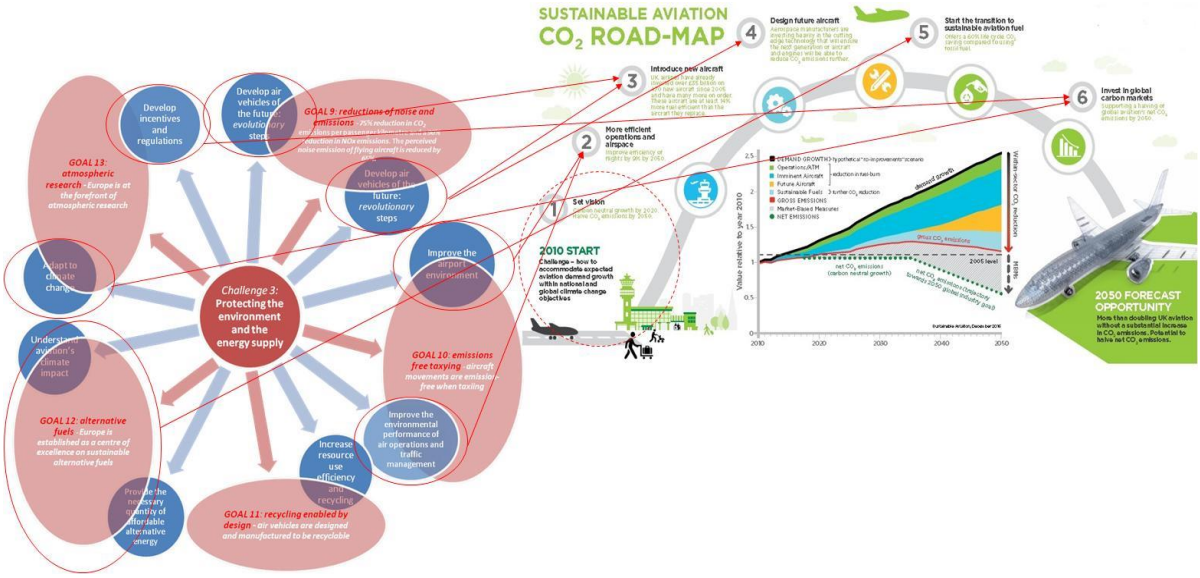


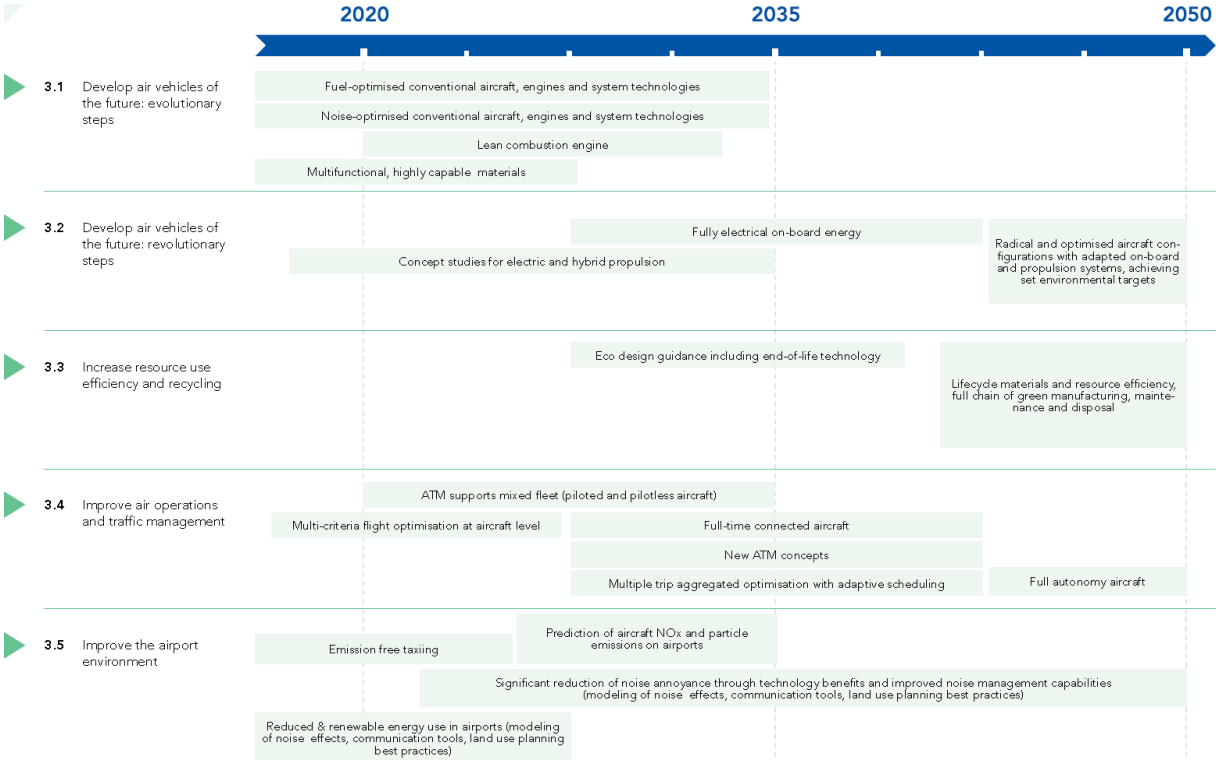
Figure 4.20: The goals and action areas for *ACARE Challenge 3* in relation to fuel/energy consumption & GHG reduction along Sustainable Aviation Roadmap 2050 [Zaporozhets O., Isaienko V., Synylo K., 2020]

Environmental impact factor from aviation	ICAO Policy Goals [ICAO Resolution A40-17, 2019]	EU ACARE Goals	US FAA and NASA Goals [NSTC2010, 2010, ASCENT Project 037, 2015]
Noise	***Limit or reduce the number of people affected*** *by significant aircraft noise*	perceived noise emission of flying aircraft ***is reduced by 65%***	***52 dB reduction*** relative to cumulative margin of ICAO/FAA Stage 4 noise limit(a 25-year goal, by enabling N+3 aircraft and engines)

NO_x emissions	***Limit or reduce theimpact of aviation emissions*** *on local air quality*	***90% reduction*** in NO_x emissions	**80%** ***reduction*** in NO_x emissions (for cruise relative to 2005 best in class and relative to ICAO CAEP/6 standard)
GHG emissions and fuel/energy consumption	***Limit or reduce the impact of aviation GHG emissions*** *on the global climate*: a ***reduction in net aviation CO_2 emissions of 50%*** by 2050, relative to 2005 levels	***75% reduction in CO_2 emissions*** per passenger km, relative to typical new aircraft in 2000	***60% reduction in Aircraft Fuel/Energy Consumption*** (*CO_2 emissions per passenger km)* relative to 2000 best in class

Table 4.4: Comparison of long-term goals for environmental impact factors of aviation between the Policy of ICAO, EU and USA on Research and Development [Zaporozhets O., Isaienko V., Synylo K., 2020]

Climate change could pose a significant financial and operational risk for the aviation industry, although there remain uncertainties as to the extent, severity and timing of impacts. The timeline for *Challenge 3* is shown in Figure 4.21 [SRIA, 2017].



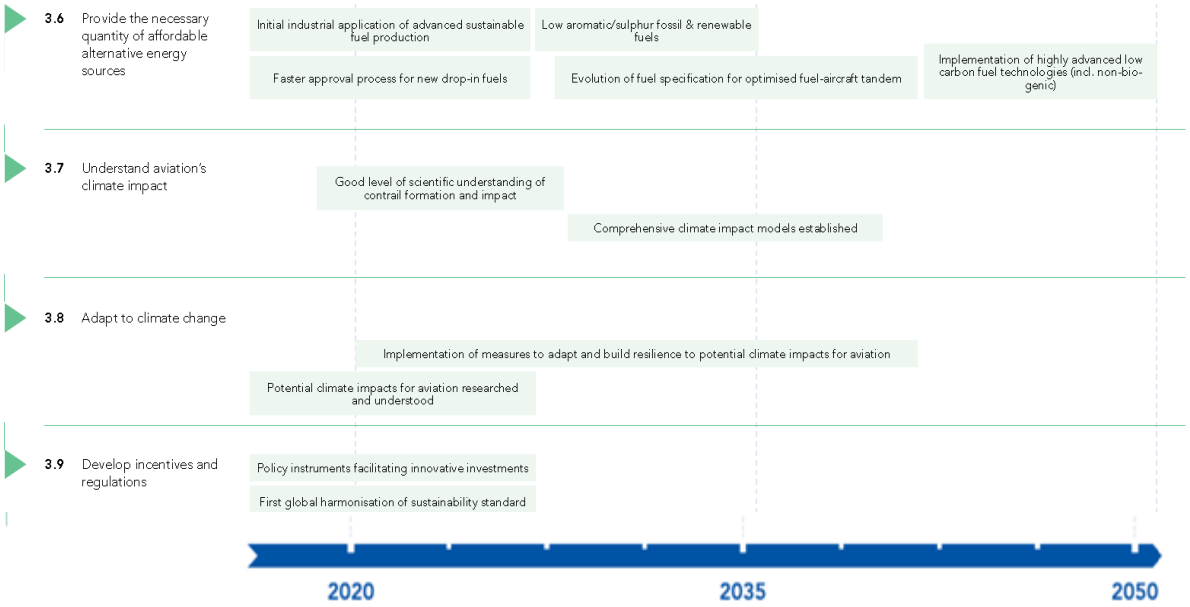


Figure 4.21: Timeline for ***Challenge 3***: Protecting the environment and the energy supply [Strategic Research and Innovation Agenda, 2017]

CAEP continuously works on aircraft/engine technologies development, currently its independent expert integrated review covers the medium-term (2027) and long-term (2037) technology goals [ICAO CAEP/8-IP/11, 2010; ICAO CAEP/9 meeting, 2013; ICAO Doc 10127, 2019], which should provide a maximum compatibility between the safe and orderly development of civil aviation and the quality of the environment.

4.1 Reduction of Noise and Emissions

** Flightpath 2050 goal 9: "In 2050 technologies and procedures available allow a 75% reduction in CO_2 emissions per passenger km and a 90% reduction in NO_x emissions. The perceived noise of flying aircraft is reduced by 65%. These are relative to the capabilities of typical new aircraft in 2000".*

This goal covers noise and emissions. The distinction is made between engine (4.1.1) and aerodynamic (4.1.2) noise and local (4.1.3) and global (4.1.4) emissions.

Historically, three major drivers have existed for aircraft technological innovation. *One major driver was fuel cost.* Previous studies [Lee, J.J., Lukachko, S.P., Waitz, I., 2004, Greene D.L., 1992] examined the improvement in aircraft fuel efficiency. Since fuel costs account for 20% to as high as 50% of the direct operating cost of aircraft, both manufacturers and airlines are highly interested in fuel-saving technologies that reduce their operating cost.

The *second type of driver* is the current movement on global *climate change and sustainability*. Over the past 10 years, the aviation sector has received attention regarding the jet emissions' potential impact on global warming and local atmosphere [Simoes A.F., Schaeffer R., 2005]. As sustainability has become a major issue for the aviation sector, both aircraft manufacturers and airlines are focused on technological and operational means to mitigate aviation's climate impact (Table 4.5).

Technology	Operations	Infrastructure	Biofuels and Economic measures

New airframe and engine technologies	Improved operationalprocedures	More efficient air trafficmanagement	Global offset mechanisms
Retrofits	More efficient flight procedures	More efficient airports	Positive economic incentives
Sustainable aviation fuels	Weight reduction		Public-private initiatives

Table 4.5: Global strategies for reducing aviation fuel uses and emissions [Fregnani J.A.T.G., Mattos B. S., 2016]

The third type of innovation driver for aircraft performance is social demand. Aircraft noise was known to cause hearing impairment in the 1960s and public demand for quieter aircraft accumulated overtime. Governments responded by phasing out noisy aircraft and eventually today's aircraft are several times quieter than earlier jet aircraft [Waitz I.A., Lukachko S.P. , Lee J.J. , 2005]. On the contrary, aircraft fuel economy, which is a surrogate measure of jet engine emissions (mostly CO_2), improved slowly during the same period. One factor for this phenomenon is the low level of social awareness on aviation and climate issues [Lee J.J., 2010].

The 36th Session of the ICAO Assembly in 2009 adopted the statement of continuing ICAO policies and practices related to environmental protection, which is supported till now [ICAO Resolution A40-17,-18,-19]. Under this scope, the Group on International Aviation and Climate Change (GIACC) formalized ICAO Council these initiatives from the industry commitment and recommendations, mostly based on the Four Pillars proposal [GIACC, 2009]. GIACC was therefore tasked with developing and recommending to the Council an aggressive Programme of Action on International Aviation and Climate Change and a common strategy to limit or reduce greenhouse gas emissions attributable to international civil aviation. The group has recommended the following potential areas of development and investments to the Contracting States defined as follows:

1.***Investment in new technologies***: Measures in this category may include purchase of new aircraft, retrofitting and upgrade improvements on existing aircraft, new designs in aircraft/engines, fuel efficiency standards and alternative fuels. Some of these measures have the potential for very high gains in fuel efficiency/emissions reduction but the costs are likely to be high with a long timeframe for implementation.

2.***Development of efficient operations***: These measures include minimizing weight, improving load factors, reducing speed, optimizing maintenance schedules, and tailoring aircraft selection to use on particular routes or services. This area is essentially a matter for aircraft operators who will make their decisions based on commercial factors in their operational scenarios.

3.***Investment on effective infrastructure***: These measures mean more efficient air traffic management planning, ground operations, terminal operations (departure and arrivals), en-route operations, airspace design and usage, and air navigation capabilities are measures with potential for relatively short to medium-term gains although the scale of potential relative gains is low to medium. In addition, more efficient planning and use of airport capacities, construction of additional runways and enhanced terminal facilities, and clean fuel operated ground support equipment to be implemented in the short to medium-term, but potential emission reduction gains are likely to be low. Increased airport capacity may also encourage increased emissions from aircraft unless appropriate actions are taken to address the emissions.

4.***Positive economic measures***: These measures include voluntary carbon offsetting, emissions trading schemes (MBM – MarketBased Measures), emissions charges and positive economic incentives. Measures in this category have potential for achieving gains in term of reductions in net emissions.

5.***Regulatory and others***: Measures that include regulatory enforcements on carbon emissions reduction (i.e. aircraft movement caps/slot management) and other initiatives such as enhanced weather forecasting, transparent carbon reporting and education/training programs.

The development of new operational procedures and techniques are relevant but limited to the current technological limitations. Fuel conservation programs are widely set by airlines and improvements are set observed on the magnitude of 5% to 10% at most. This represents a significant improvement with relatively small amounts of investments and airlines are constantly encouraged to optimize their operations on Fuel Conservation initiatives.

However, the first of the four pillars (new technologies) is considered nowadays as the main potential contributor for achieving the desired ICAO objectives in emission reduction. Its achievement strongly depends on the development and implementation of new technologies by aircraft, engine and equipment manufacturers, using higher fidelity aircraft design tools. The main areas have a direct impact on fuel efficiency are envisioned to be airframe (aerodynamics, structures, equipment systems and new configurations) and engines technologies. Nowadays, a large number of individual technologies are under consideration for implementation in future aircraft and engines. For example, a study conducted in 2013 by IATA [IATA Technology Roadmap, 2013], the German Aerospace Center (DLR) and the Aircraft System and Design Laboratory (ASDL) of the Georgia Institute of Technology launched the Technology Roadmap for Environmentally Sustainable Aviation (TERESA) [Nolte P., et al., 2012]. The objective was to quantify the expected benefits of the implementation of individual technologies in an operational framework, considering a typical world fleet. Each new generation of aircraft yields a typical 15% fuel efficiency improvement compared to the generation it replaces, Table 4.6. This replacement occurs on average every 20 years, although smaller serial improvements and retrofits occur in the intervening period. Current NASA's Technological Readiness Levels (TRL) are considered to estimate the availability of each proposed technology. Tables 4.7 and 4.8 contain the list of proposed technological improvements (airframe and engines related) and their associated fuel efficiency reduction. It is noticeable that up to 30% reduction on 2005 levels on fuel efficiency may be achievable after 2020, most of them related to engines technologies.

Seat category	Aircraft Category	2010 reference	New generation (examples)	Entry into service	Fuel saving reference
51 – 100	Regional jet	ATR/CRJ	MRJ	2020	20%
		E-Jet	E-Jet E2	2020	24%
101 – 210	Narrow body	A320/B737	A220/A320neo/B737 MAX	2016/2017	20%
211 – 300	Widebody	B767	A350/B787	2015/2011	20%–25%
301 – 400		A330/B777	A330neo/B777X	2018/2019	14%–20%
401 – 500		A380/B747-8	A330neo/B777X	2018/2019	14%–20%

Table 4.6: New generation aircraft recently introduced or about to enter the market (before the end of 2020) [IATA FactSheet, 2019]

Jet noise, which previously used to dominate, is now significantly lower, because of the lower fan pressure ratio (accompanied by higher bypass ratio) producing lower jet velocity. A list of technology factors is summarized in Table 4.9 for airframe and engine technologies. A technology factor is a mathematical description used to model the technology impact within the physics-based environment. Finally, it is worth to mention that environmental benefits of new technologies (through a better fuel efficiency and thus lower carbon emissions) will become effective through airline fleet modernization and, to a minor degree, retrofits to in-service aircraft. There is an underlying challenge to select the appropriate technologies as this selection are driven by uncertain factors such as their current development status, benefits, risk and their research and development costs. In summary, aircraft design techniques under the environmental perspective became significantly relevant throughout the last decade, driven by the industry commitment on emissions

reductions set by ICAO goals. The inclusion of fuel efficiency focus on the design framework is a key parameter on the next aircraft generations.

Group	Concept	Technology	Applicability	Fuel Reduction Benefit	Technology Readiness Level 24 in 2014	Expected Availability
Aircraft Configuration	Truss braced wing		After 2020	10 to 15%	2	2028
	Hybrid wing-body		After 2020	10 to 15%	4	2026
	Cruise efficient stall		After 2020	< 1%	3	2027
	Flying without landing gear		After 2030	10% to 20%	1	2032
Aerodynamics	Advanced Wingtip	Wingtip fence	Retrofit	1% to 3%	9	2012
		Blended winglet /Sharklets	Retrofit	3% to 6%	9	2012
		Racked wingtip	Retrofit	3% to 6%	9	2012
		Split winglets (scimitar tips)	Retrofit	2% to 6%	7	2022
		Spiroid wingtip	After 2020	2% to 6%	7	2022
	High Lift Devices	High lift / Low Noise	After 2020	1% to 3%	4	2026
		Variable Camber Trailing Edge	Before 2020	1% to 2%	9	2012
		Dropped spoiler	Before 2020	1% to 2%	9	2012
		Hingeless flap	After 2030	1% to 2%	3	2027
	Drag reduction	Drag coating	Retrofit	< 1%	9	2012
		Turbulent flow coating (riblets)	Retrofit	1%	8	2015
		Graphic Films	Retrofit	1%	9	2012
	Natural Laminar Flow		After 2020	5% to 10%	7	2022
	Hybrid Laminar Flow		After 2020	10% to 15%	7	2022
	Variable Camber		Before 2020	1% to 3%	8	2015
	Variable Camber with new control surfaces		After 2020	1% to 5%	5	2024

Table 4.7: Airframe technologies development impact and expected availability for introduction

Noise belongs to the everyday life in urban environments. Unfortunately, aircraft has a large number of noise sources, as illustrated in Figure 4.22. The major sources of engine noise are the fan and jet, and to a lesser extent, the compressors, combustor, turbine and bleeds (which may actually dominate at certain times during flight), Figure 4.23. Airframe noise is generated by the airflow surrounding the moving plane. The main sources are the discontinuities of the aircraft structure, such as high-lift devices (HLD), landing gear wheels (when extended), and trailing edges which lead to speed shearing (aircraft speed versus still air). A further source of noise arises from the interaction of the engines exhaust jet with the airframe. As a general rule, engine sources dominate on take-off while airframe noise dominates on approach.

Group	Concept	Technology	Applicability	Fuel Reduction Benefit	Technology Readiness Level in 2014	Expected Availability
New Engine Architecture	Geared Turbofans		Before 2020	10%-15%	7	2016
	Advanced Turbofans		Before 2020	10%-15%	7	2016
	Counter rotating fan		After 2020	15%-20%	3	2019
	Open Rotor		After 2020	15%-20%	5	2019
	New engine core concepts		After 2030	25%-30%	2	2026
	Embedded Distributed Fan		After 2030	Less than 1%	2	2026
Advanced Concepts	Fan	Component Improvements	Before 2020	2%-6%	8	2013
		Zero Hub	Before 2020	2%-4%	7	2016
		High BPR	Before 2020	2%-6%	7	2016
		Variable Nozzle	After 2020	1%-2%	7	2016
	Combustor	Variable Flow Splits	After 2020	1%-2%	5	2020
		Ultra compact low emission	Before 2020	1%- 2%	5	2020
		Advanced	Before 2020	5%-10%	8	2013
	Compressor	Bling concept	After 2030	1%-3%	3	2023
		Bisk Concept	After 2020	1%-3%	7	2016
	Variable Geometry Chevron		After 2020	Less than 1%	5	2020
Nacelles and Installation	Buried engines		After 2020	1%-3%	5	2020
	Reduced nacelle weight		Before 2020	1%-3%	7	2016
Engines Cycles	Adaptive Cycles		After 2030	5%-15%	2	2030
	Pulse Detonation		After 2030	5%-15%	2	2030
Others	Boundary Layer Ingestion Inlet		After 2020	1%-3%	3	2023
	Ubiquitous Composites		After 2020	10%-15%	3	2023
	Adaptive flow control		After 2020	10%-20%	2	2026

Table 4.8: Engine technologies development impact and expected availability for introduction

Airframe			Aircraft Engine		
	Min, %	Max, %		Min, %	Max, %
Δwing weight	-30	+20	ΔSFC	-20	+10
Δfuselage weight	-30	+10	Δengine weight	-20	+10
Δempennage weight	-10	+10	Δsize	0	+10
Δhydraulics weight	-100	0			
Δelectrical weight	0	+20			
Δcabin weight	-40	0			
ΔAPU	-100	0			
Δwater weight	-10	0			
ΔL/D	0	+25			
Δinduced drag	-20	0			
Δfriction drag	-25	0			

Table 4.9: Technology Factors Airframe and Aircraft Engine

There is potential for reducing noise by way of better component design and incremental improvements in existing technology, but it is not appropriate to detail all the possibilities here (Table 4.10 is for illustrative examples). Instead, we highlight where new technological improvement is likely, and cases where an improvement in aircraft efficiency and gaseous emissions creates a new noise risk that will need to be addressed. However, they can be broadly classified as engine noise sources and airframe noise sources. The range of liners employed to attenuate noise will be significant in the near term. Specifically, lip liners (where the intake liner is extended around the lip of the nacelle intake) are feasible now that the problem of integrating them with the de-icing system has been overcome. Modern ceramics and improved manufacturing have made core exhaust liners possible, but the problem of high temperatures and a highly curved geometry must still be solved. Equally, ALM allows for varying the depth of nacelle liners to obtain a

distribution of acoustic impedance that can be optimised for maximum attenuation (Nark et al., 2016) or the use of radically new liner design (Koch et al., 2017).

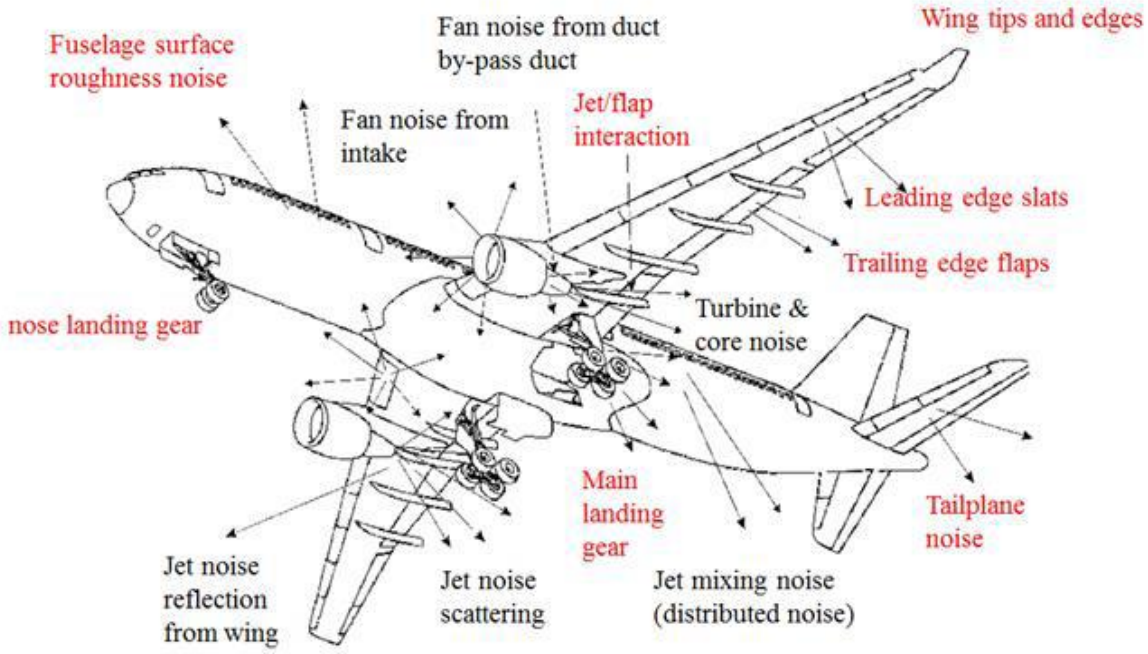


Figure 4.22: Main sources of engine and airframe noise

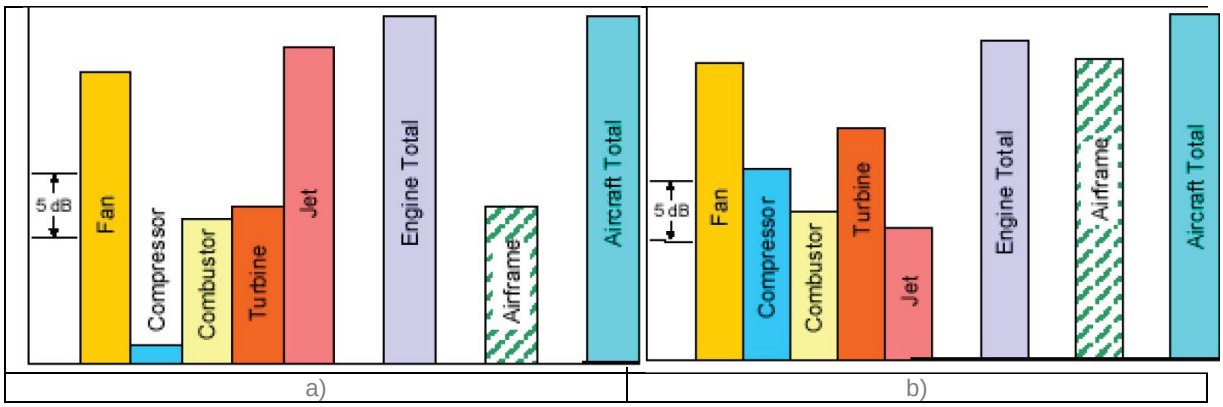


Figure 4.23: Sources of acoustic emission during: a) takeoff; b) landing [Leylekian, L., Lebrun, M., Lempereur, P. 2014]

Whilst technological improvements targeted at reducing noise and/or gaseous emissions have been made, the main reason for the steady progress in reducing aviation emissions over the last few decades can be directly linked to an overall improvement in aircraft fuel consumption, as illustrated in Figure 4.24.

Aircraft efficiency is a measure of how well the available energy of the fuel is converted into useful forward motion for an aircraft. It is the product of the individual efficiencies of the steps involved in this overall process. The efficiency of an engine comprises two main factors. The engine's thermal efficiency describes the effectiveness with which the available chemical energy in the fuel is turned into mechanical energy, and the propulsive efficiency of the engine indicates how well the mechanical energy is turned into thrust. Additionally, the propulsive efficiency of the airframe measures how well this thrust is converted into useful forward motion. Higher values for all of these efficiencies are desirable in the drive to reduce fuel-burn and CO_2 emissions. However, while lower fuel burn implies less NO_x emission, the higher thermal efficiency can lead to enhanced NO_x production per unit mass of fuel burn.

Component	Technology	Estimated dB Reduction on component level	Timescale	Notes
Fan	Rotor Sweepn and Stator sweep and lean	2dB	Near term	
	Variable Area Nozzle	2dB	Near term	Complexity and weight issues
	Liner improvements	2--4dB	Near term	Manufacture & repair technologies. Integration with other systems such as de-icing.
	Active stators	Up to 8dB	Near/Long term	Highly complex. Weight & structural integrity issues.
	Active blade control	Up to 20dB	Near/Long term	
Jet	Chevrons	1 -- 3dB on TO	Near term	Potental fuel burn penalty
	Fluid injection/microjets/excitation	1--3dB	Near/Long term	Highly complex.
Landing Gear	Fairings	Up to 3dB	Near term	Weight penalty. Maintenance access.
	Low noise design	Up to 5dB	Near/Long term	
	Flow control	1dB	Near/Long term	Weight penalty.
High Lift Devices	Slat & track treatment	Up to 5dB	Near term	Potential for increased drag => fuel penalty
	Flap side edge treatment	Up to 5dB	Near term	Potential for increased drag => fuel penalty
	Low noise design	Up to 5dB	Near/Long term	Potential for increased drag => fuel penalty
Core	Hot liners	2--4dB	Near term	

Table 4.10: Examples of potential noise reduction through component improvements. (Based on data given in [CAEP/9 Meeting, 2013])

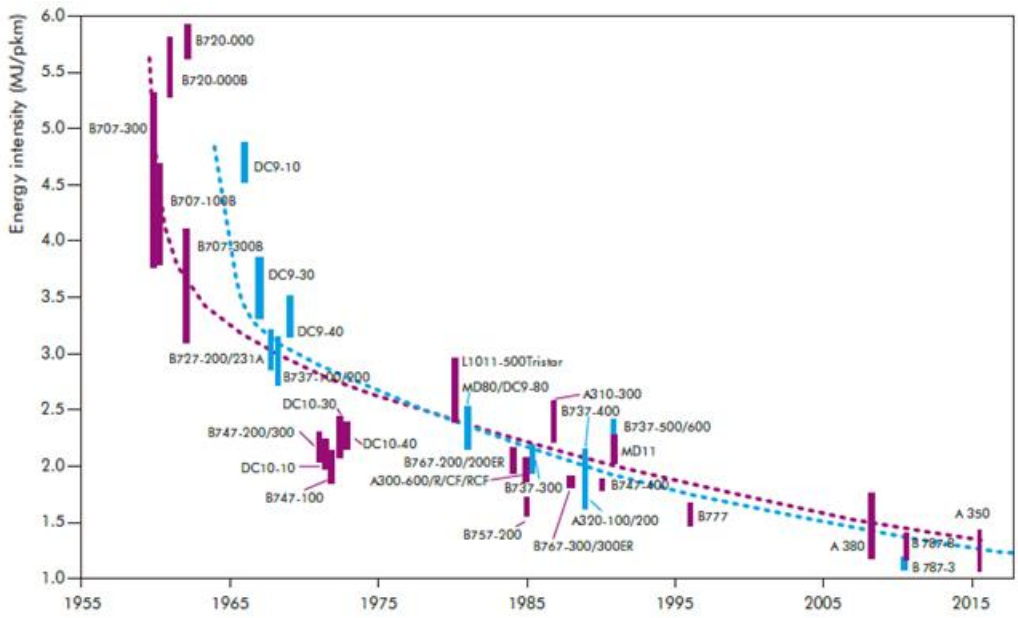


Figure 4.24: Improvement in aircraft efficiency

Historically, the greatest increase in aircraft efficiency has been made by improved engine performance. As the engines being installed on large aircraft continue to grow in size, the aircraft noise becomes more sensitive to specific features of design, including engine integration, aerodynamics, mass, and interaction effects-the level of interdependence therefore increases. However, as engines have become more efficient, the gains to be made through airframe improvements have become more significant. There are two main points worth noting here. Aircraft weight is a primary driver of fuel burn because a heavier aircraft requires increased lift, thereby increasing drag and the consequent need for additional thrust. To decrease weight, the use of composite materials (based on carbon fibre or glass fibre) in aircraft has increased in recent decades. A high percentage of newer aircraft such as the Boeing 787 and the Airbus A350 XWB consist of such materials (in Figure 4.24 the best results in fuel efficiency among the whole aircraft fleet).On 14 February 2019, Airbus announced their A380s have been cancelled, with production ending in 2021, after 12 long years

of shaky business and development. One of the reasons for such a decision is: A380's operating costs were almost twice as much as other big airliners, eating up almost $30,000 of fuel every hour while in flight – compare this to the efficiency of a Boeing 787-9, costing around $15,000 an hour (in fuel prices in February 2019).

Boeing 787-9 airliner is more efficient energetically than the larger Boeing 777, Airbus A380 and Boeing 747-400. The key to the exceptional performance of the Boeing 787 Dreamliner is its suite of new technologies and its structural design, which includes high flexible wings. Composite materials make up 50 per cent of the primary structure of the 787, including the fuselage and wing. Boeing 787 an innovative systems architecture that is simpler, more functional and more efficient than that of other aeroplanes. For example, onboard health-monitoring systems monitor and report systems maintenance requirements to ground-based computer systems. Advances in engine technology are the biggest contributor to overall fuel efficiency improvements on the Dreamliner. The Boeing 787 is fitted with new engines that feature increased by-pass ratio, higher overall pressure ratio, advanced materials, and electric start. The design and build process of the Boeing 787 has added further efficiency gains. For example, manufacturing the Boeing 787 fuselage as one-piece sections eliminated 1,500 aluminium sheets and 40,000-50,000 fasteners per section [Fregnani J.A.T.G., Mattos B. S., 2016].

Boeing 787 reflects a completely new approach to onboard systems. Virtually everything that has traditionally been powered by bleed air from the engines has been transitioned to an electric architecture. The affected systems include: Engine start; Auxiliary power unit (APU start); Wing ice protection; Cabin pressurization; Hydraulic pumps.

The only remaining bleed system on the Boeing 787 is the anti-ice system for the engine inlets. The auxiliary power unit (APU) provides an excellent illustration of the benefits of the more electric architecture. One of the primary functions of a conventional APU is driving a large pneumatic load compressor. Replacing the pneumatic load compressor with starter generators results in significantly improved start reliability and power availability. The use of starter generators reduces maintenance requirements and increases reliability due to the simpler design and lower parts count. In terms of inflight start reliability, the Boeing 787 APU is expected to be approximately four times more reliable than conventional APU s with a pneumatic load compressor [Fregnani J.A.T.G., Mattos B. S., 2016].

Another fundamental architectural change on the Boeing 787 is the use of variable frequency electrical power and the integration of the engine generator and starter functions into a single unit. This change enables elimination of the constant speed drive (also known as the integrated drive generator, IDG), greatly reducing the complexity of the generator. In addition, by using the engine generator as the starter motor (an approach used with great success on the Next-Generation 737 APU), the Boeing 787 has been able to eliminate the pneumatic starter from the engine. When compared to the more complex Boeing 767 IDG, the Boeing 787 starter generator is predicted to have a mean time between faults (MTBF) of 30,000 flight hours - a 300 percent reliability improvement compared to its in-service counterpart [Fregnani J.A.T.G., Mattos B. S., 2016].

The medium-range aircraft class has seen significant re-engineering over the last two decades with the introduction of aircraft such the A320neo and B737 Max, while three all-new wide-body long haul models – the A380 and A350, plus the B787 – have been introduced. They have benefited from the introduction of new technologies, principally the increasing use of composites and the replacement of hydraulic and pneumatic systems by electric-powered alternatives. Given these newly introduced wide-body aircraft and the fact that both manufacturers have large backlogs in their narrow body programmes, we are unlikely to see wholly new replacement aircraft in either class in the near future, probably 2030.

The increasing use of electric systems heralds yet further introduction of electric technology, and the commitment of both Airbus and Boeing to electric power is clear with the E-Fan and Horizon X programmes.

More broadly, there exist a host of concepts and demonstrators for hybrid electric and fully electric-powered aircraft by a number of new players who have entered the field.

The notion of "on-demand" (or "air taxis") is currently seen as a likely first step for fully electric flight, with hybrid electrics replacing the current family of regional turbofan and turboprop aircraft (such as the Bombardier CRJ and Q400 Series, and the Embraer E jet series). Uber recently announced plans to introduce electric air taxis (the Uber Elevate) by 2023, but the use of hybrid electric-powered regional aircraft is more likely EIS in the 2030s timeframe. It should also be noted that a new type of electrically powered aircraft already with us is the small UAV or drone. Likely, the use of drones will substantially increase over the years to come.

In addition to decreasing weight, decreasing drag (for a given thrust) will improve aircraft efficiency. Winglets are the most obvious recent example of a technology that decreased drag. Adding winglets that are tilted upward at the tips, either to new aircraft or as retrofits to existing models, has delivered 3-5% reductions in fuel burn, depending on the length of the flight and type of aircraft. An alternative to the winglet is the raked tip, which can produce similar drag reductions. One more way of doing this is to increase the aspect ratio of the wing (i.e. make it longer and thinner). With a conventional cantilever wing arrangement, there are limits to how far this approach can be pursued because of structural integrity concerns. However, with composite technology, there is now the capability to manufacture truss-braced wings (i.e. a wing supported part-way along its length by a strut which carries part of the load to the fuselage). According to NASA, such a wing can reduce fuel use by 5 to 10%. These benefits are offset by potential space-related problems at airport stands as a result of the elongated wings, increasing the likelihood that such a design will fall within the longer-term timeframe.

One drag reduction technology that is realistically achievable in the near term is the Natural Laminar Flow wings. The *EU Clean Sky BLADE* project recently conducted a demonstration to show the feasibility of introducing laminar flow wing technology on a large airliner. It is estimated that the technology can decrease aircraft drag by up to 10%. Further efficiency gains to the engine will be made via both thermal efficiency and propulsive efficiency. Like in the past, these will be achieved by further increasing the core pressure ratio and engine BPR. However, the penalties associated with these strategies (enhanced NOx production and increased weight, respectively) are now sufficiently large that mitigating technology will need to be employed.

Continuous progress is being achieved in all areas of evolutionary technologies, namely aerodynamics, materials and structures, propulsion and aircraft equipment systems. Some examples of technologies which have recently made noticeable progress are: natural and hybrid laminar flow control, new high-bypass engine architectures as well as aircraft systems such as electric landing gear drives and fuel cells for onboard power generation. By applying combinations of evolutionary technologies, fuel efficiency improvements of roughly 25 to 30% compared to today's aircraft still appear possible. However, further improvements of the tube-and-wing configuration powered by turbofans are becoming more and more difficult to conceive around 2035.

In the longer term towards 2050, radically new aircraft configurations will be required to reduce fuel burn and carbon intensity significantly. The novel airframe configurations that are currently seen as most promising are the strut-braced wing, the blended wing body, the double-bubble fuselage and the box-wing aircraft. While for a long time blended wing bodies were thought to be a solution optimized for very large aircraft of several hundred seats, it has recently become realistic to design small blended wing bodies of 100 to 200 seats. On the one hand, they do not have the same drawbacks as their large counterparts in terms of airport compatibility and passenger acceptance. On the other hand, they allow improved boarding time and passenger comfort.

The most promising propulsion technologies are open rotors, boundary layer ingestion and electric aircraft propulsion. Due to their large weight per unit of stored energy, batteries as primary energy storage for aircraft propulsion place limitations on the size and range of fully battery-powered aircraft. Various categories of

hybrid-electric aircraft propulsion exist as well, which use liquid fuel as a primary energy source. They benefit from the high energy efficiency of electric motors and use batteries as an additional energy source for peak loads. Today, several electrically-powered general aviation aircraft types are already in operation. Specialized start-up companies work on 15 to 20-seaters for the next decade and 50 to 100-seater regional aircraft, announced for entry into service around 2035. Even though this time scale seems optimistic, it shows the stepwise scalability of electric aircraft technology, which helps reduce its development risk. While today about 65% of electricity generation comes from fossil sources and produces significant amounts of CO_2, the share of renewable electricity will likely increase noticeably in the next decades, thanks to governments' and industries' current focus on climate action throughout all sectors.

4.1.1. Engine Noise for Turbofans and Propfans

Noise still represents a major challenge for all sectors of the aviation industry and ongoing research is needed to reduce its impact on society [SciCom, 2019]. Since the start of the jet age, enormous progress has been made in lowering noise levels (Figure 4.25) and reducing the noise footprint per aircraft movement. Only in the last 15 years alone Rolls Royce and other engine manufacturers have continued to improve aircraft engine design, resulting in a sustained reduction in noise each time a new aircraft engine is introduced, as illustrated in Figure 4.26, and, of course, supporting new standard influence on aircraft noise exposure reduction around the airports. Aircraft produced today are 75% quieter than those of 50 years ago. These new quiet aircraft typically output half the noise of the aircraft they are replacing, so air traffic movements can double without increasing the total noise output. In more detail, a report [Sustainable Aviation Noise Road-Map, 2018] predicts that as current aircraft are replaced by '*Imminent*' and '*Future*' aircraft, the noise exposure from UK aviation reduces by around 20% (Figure 4.27), which is close to EU forecasting (Figure 4.11).

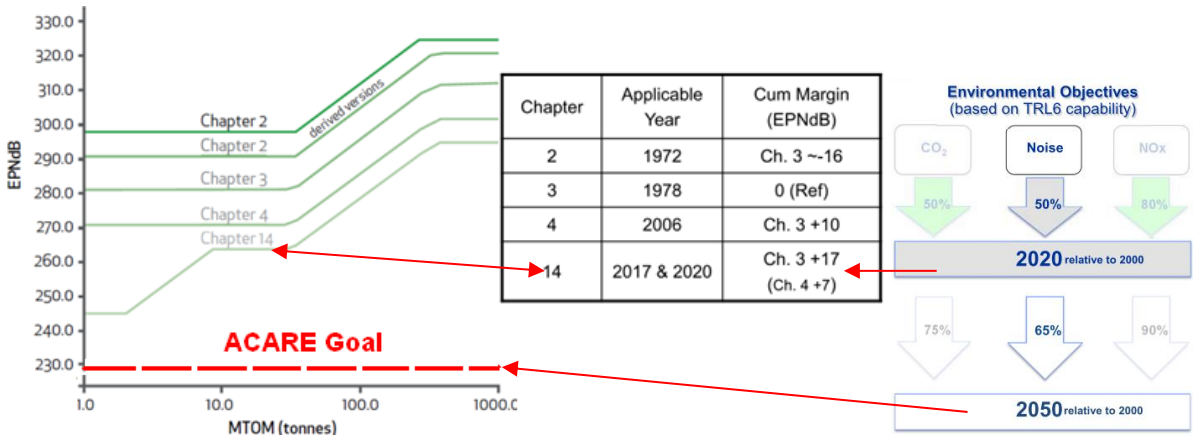


Figure 4.25: ICAO requirement to aircraft noise and ACARE 2050goal

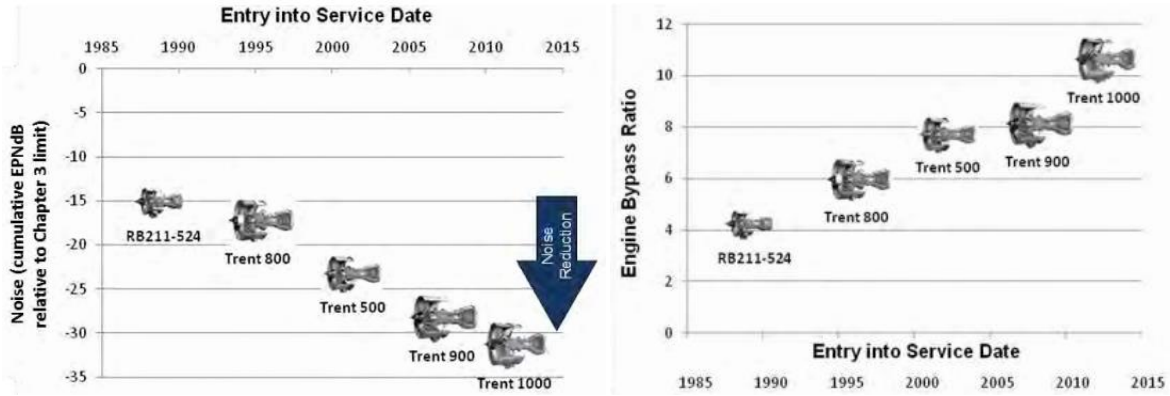


Figure 4.26: Development of Quieter Rolls Royce Aircraft Engines [Sustainable Aviation Noise Road-Map, 2018]

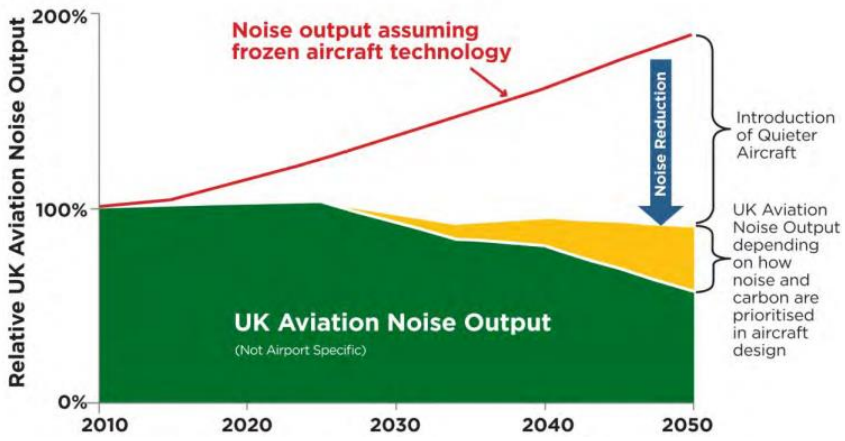


Figure 4.27: Forecast Changes in UK Aviation Noise Output between 2010 and 2050

During the 50 years of aircraft noise standardization from ICAO (1st Edition of Annex 16 – Aircraft Noise was in 1969) Chapter 2 to 14 the cumulative decrease was reached up to ~35 dB, close to this value is necessary to be reached till the ACARE noise goal at 2050. In 2014, ICAO adopted a new (latest) standard that will result in a reduction of 7 EPNdB compared to the Chapter 4 Standard, so in-production aircraft are prohibited to be manufactured with noise higher than Chapter 14 requirements. The global situation of noise technology research initiatives as of December 2018 is summarized in Figure 4.28.

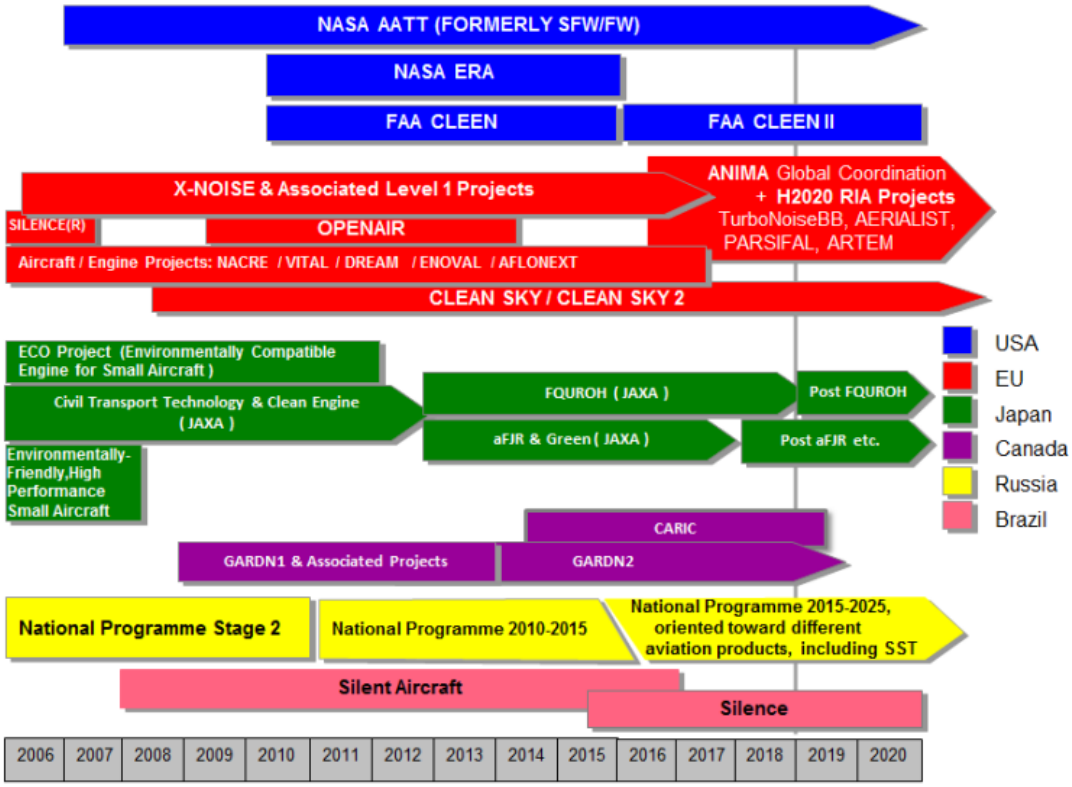


Figure 4.28: Committed major national/regional initiatives as of end 2018

It covers a 15-year period (2006-2020), and provides an evolutionary perspective, indicative of the worldwide commitment to continuously support the technology side of ICAO's Balanced Approach.NASA's Advanced Air Transport Technology (AATT) project has numerous technical challenges related to noise reduction (Table 4.11). Its objective is to demonstrate TLR4-6, looking toward mature technology solutions in the 2035 –

2045 timeframe. The noise reduction technical objectives target 22-32dB (below Stage 4 US FAR or Chapter 4 ICAO) in the near-term (2015-2025), 32-42dB in the mid-term (2025-2035) and 42-52dB in the far term beyond 2035.The FAA CLEEN II program looks at more mature noise reduction technologies to demonstrate TRL 6-7. The objectives of CLEEN II include demonstrating certifiable technologies to meet the environmental targets of 32dB below Stage 4 US FAR/Chapter 4 ICAO by 2020. While CLEEN II will be ending in 2020, CLEEN III plans to pick up with new projects solicitations expected in 2019.

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near Term 2015-2025	Mid Term 2025-2035	Far Term beyond 2035
Noise (cum below Stage 4)	**22 - 32 dB**	**32 - 42 dB**	**42 - 52 dB**
LTO NOx Emissions (below CAEP 6)	**70 - 75%**	**80%**	**> 80%**
Cruise NOx Emissions (rel. to 2005 best in class)	**65 - 70%**	**80%**	**> 80%**
Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)	**40 - 50%**	**50 - 60%**	**60 - 80%**

Table 4.11: NASA AATT technology objectives

In July and August of 2018, Boeing completed the Quiet Technology Demonstrator 3 (QTD3) flight test under the NASA AATT program to demonstrate and increase the TRL of the low-drag Multi-Degree of Freedom (MDOF) acoustic lining in the inlet. Introduction of the low-drag lining technology led to a 3.4 EPNdB cumulative benefit on measured inlet noise when compared with a standard production liner (see Figures 4.29, and Table 4.12).

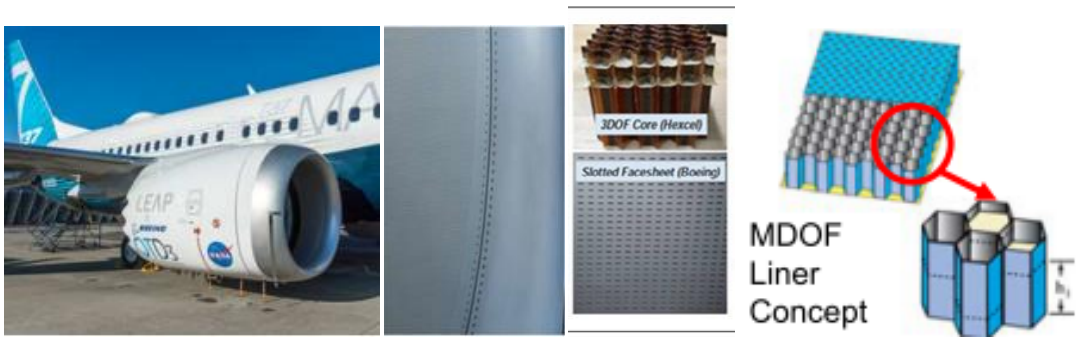


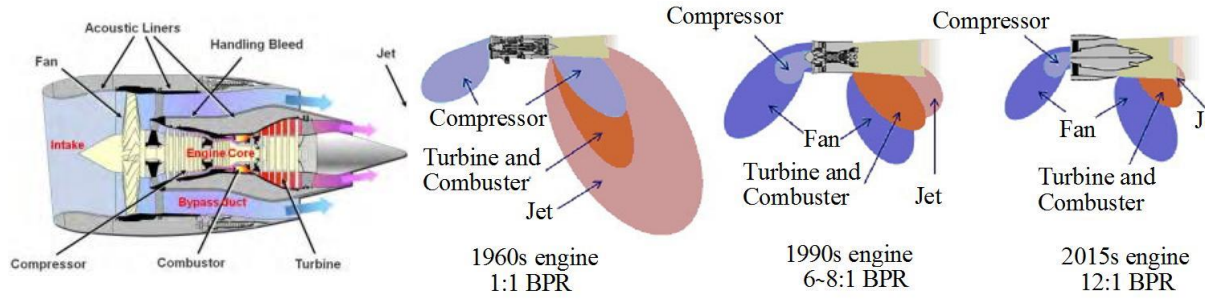
Figure 4.29: MDOF hardware tested and noise measurements taken

Some of this progress has been offset by air traffic growth that can lead to increased total noise exposure unless noise reductions continue. The actual noise output will vary by airport, depending on the fleet mix, route structure, number of runways, operating restrictions and the scope for adopting new operational procedures to reduce noise. Therefore it is not possible to draw direct comparisons between the indicative trends illustrated here and the future noise footprints of any specific airport. The major contributor to the reduction of engine noise has been the increase in the by-pass ratio of turbofan engines: the larger by-pass flow at a lower speed radiates less noise and shields and scatters the sound from the hot high-speed core flow. Increasing the by-pass ratio also decreases fuel consumption, leading both to lower emissions and more favourable economics. This triple win-win-win situation of lower fuel consumption-less noise-lower emissions may be reaching its limits for by-pass ratios (BPR) in the range 15-20.

Condition	Approach	Cutback	Takeoff	Cumulative
Benefit (re Production Liner)	0.6 EPNdB	1.5 EPNdB	1.3 EPNdB	3.4 EPNdB

Table 4.12: Inlet measured component noise reduction

The engine has traditionally been the major source of noise (jet noise and fan/turbine/compressor turbo machinery noise have been predominant, with other engine noise sources such as combustors and handling bleeds now becoming significant). The problems of reducing the acoustic emission and improving of fuel efficiency of aircraft engines and aircraft as a whole are interconnected and are currently the most relevant. The major contributor to the reduction of engine noise has been the increase in the by-pass ratio of turbofan engines (Figure 4.26): the larger by-pass flow at a lower speed radiates less noise and shields and scatters the sound from the hot high-speed core flow. In by-pass engines, the main sources of noise are the fan, jet and gas generator. Figure 4.30 shows a typical directivity pattern and qualitative distribution of noise power between the main noise sources of turbojet with varying of their bypass ratio. Thus, in current turbofans with a large bypass ratio the fan is the main source of broadband and discrete noise in upstream and downstream directions, and the jet and gas generator make a significantly smaller contribution to the overall noise level of the engine.



a) b)

Figure 4.30: Typical directivity patterns and qualitative distribution of noise power between themain sources (a) in dependence with varying bypass ratio (b) of the turbofan engines

For higher BPR the size and weight of the engine nacelle and the limited space for acoustic liners and other noise reduction measures point towards the open rotor. The propfan promises reductions in fuel consumption up to 20% corresponding to a BPR of 30-40 not feasible with engine nacelles. The reductions in fuel consumption have direct benefits in lower emissions and better economics. However, increasing the bypass ratio further, whilst delivering additional jet noise reductions, would not deliver such significant reductions in aircraft noise due to other noise sources (especially fan noise) becoming dominant. Such ultra-high-bypass-ratios introduce additional design challenges including the increased engine installation drag and weight, the mechanical design of the fan, and the aerodynamic performance of the fan, compressor and low-pressure turbine.

Techniques for reducing jet noise without increasing bypass ratio involve promoting faster mixing of the jet exhaust with the atmosphere whilst minimising the turbulence created in the mixing process. Such treatments bring with them potential aerodynamic and mechanical design challenges, and there is a trade-off between noise benefits and potential fuel-burn penalties. Nozzle lip treatments (such as the serrations featured in the flight testing of the Rolls-Royce/Boeing Quiet Technology Demonstrator (Figure 4.31a) and the Rolls-Royce/Airbus 'low interior noise fan nozzle' research programme (Figure 4.31b)) are now entering service on various aircraft including the Boeing 787 powered by the Rolls-Royce Trent 1000.



a) b)

Figure 4.31: Chevron nozzle: a) Boeing Quiet Technology Demonstratornozzle made of shape memory material; b) Rolls-Royce/Airbus low interior noise fan nozzle

Propulsion efficiency of the jet engine is maximum when exhaust jet speed is equal to that of air vehicle that does not produce propulsion. In practice at preset propulsion, the jet speed can be reduced up to that optimum value due to increase in the bypass ratio of the engine and reduction of fan rotational speed. It also makes a favourable influence on noise. As a result the diameter of engine fan systems gradually has grown. To reduce weight and improve the aerodynamic efficiency of the fan of the last century fan blades were replaced by those made of a hollow titan. New blades are of superplastic forming, wide-chord ones and developed with the involvement of complex third-dimensional aerodynamic design. Fan protection super light ribbed systems made of titan also replaced high-priced Kevlar-coated systems. In future even lighter and more efficient fan systems should support high integrity level to be provided by a hollow titan blade and thus can have complex metallic or composite structures. Such technology is developed in VITAL EU program.

Open rotors, in essence, are turboprop engines with second counter-rotating propeller, which regenerates the flow. Addition of the second step of the propeller makes it possible to improve considerably efficiency and high speed of engine operation holding the propeller diameter, which can be built in the airframe. Without a spinner around propellers, the open rotors have a lower potential to provide shielding and releasing noise reduction than turbofan ones. Though the early results of scaled model tests show that the modern design with open rotor can be as much "soft" as currently closed turbofans. This potential effect on the perceived noise around airports should be balanced with a potential 30% increase in efficiency of fuel use over modern turbofans. Open rotors also can be restricted from the technical point in several motion speeds some lower than turbofans (maximum Mach number is equal to 0,75, but not to 0,85 that makes 5-10 minutes of additional flying time). The number of flights, which can be made at short hauls (< 2000 km) per day, does not change considerably; therefore this difference in speed will be acceptable. Nowadays some turbofan air vehicles with short ranges are already slower than M0,8 in order to save fuel. Long-time air vehicles can still support closed engines, where time, noise and operational problems can avoid application of the open rotor [Parker R., Lathoud M., 2010].

The *open contra-rotating rotors* require careful optimization both from the aerodynamic and noise aspects, with the aft rotor cutting the wake of the forward one. Taking as noise metric the average of sound level (EPNdB) at the 3 certification measuring points the prop-fan could meet current noise standards. Future noise standards could be more challenging depending on the further reductions sought below the current standard.

For example, in the framework of Quit Technologies Demonstrator 2(QTD2) program, the engine nacelle with a seamless inlet and chevron nozzle made of shape memory material of B777 aircraft with bypass turbojet engine GE90 was subjected to flight tests. The test results showed that the application of such technologies can reduce the noise level at takeoff by ~3–4 dB and improve specific fuel consumption at cruise flight conditions by 1% [Craig L., 2006, Eury S., 2005, Gliebe Ph., Dodds W., 2005].

Acoustic liners in the nacelle are important in reducing the noise from engine internal sources as it propagates along and out of the intake, bypass duct or core duct (Figure 4.32).To reduce the noise level it is supposed to use the noise active control system, which includes acoustic resonators to be installed on blades of the fan

outlet straightener and devices based on MEMS-technology and installed along the inner passage of the engine nacelle. Besides, special porous materials are under development, the use of which can reduce the acoustic emission from the source [Delfs, J.W., et al., L. 2017]. The application of such a system makes possible to reduce the noise level in a source by ~50–60% (Figure 4.32), or overall aircraft noise reduction achieved by fan forward and fan rearward noise attenuation through acoustic liners was in the range of 10 to 12 EPNdB (cumulative) on recent aircraft types[ICAO, Doc 10127, 2019].

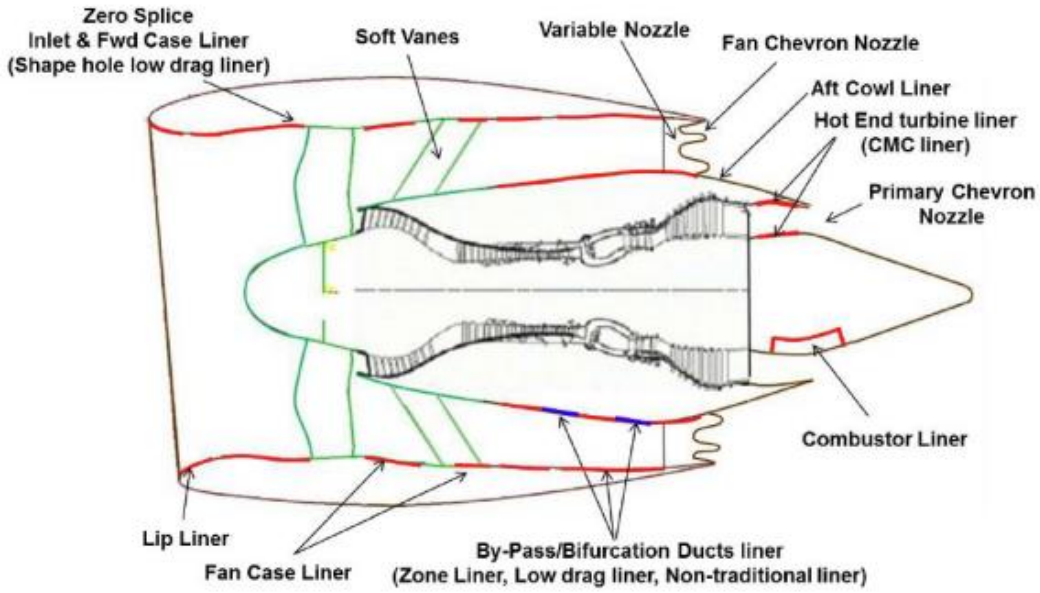


Figure 4.32: Engine noise reduction technologies [ICAO, Doc 10127, 2019]

In the work [Czech M.J.,Thomas, R.H., Elkoby, R., 2012] there were studied the effects of chevron nozzles of two main types on the noise level, chevron rigging angles (submersion), the effect from a standard pylon, vertical control surfaces of an airframe, elevon and aileron deviation angles. Sufficient noise reduction was possible in case of a combination of low-frequency noise reduction from chevrons and shielding from the redistribution of the initial peak source and rear protection space at nominal design position of the fan diameter in front of the trailing edge. Effects from additional characteristics of the airframe were generally restricted. Vertical surfaces provided noise reduction up to 1 dB, but only in restricted ranges of polar and azimuth angles. Effects of elevon deviation depended on observer's azimuth angle and also were small, though the deviation made only 5 degrees. This effect will probably increase for higher deviation angles of the elevons. A new concept of acoustic inserts built in an aileron also was tested with restricted effect, although the design was not optimized for this application. Further work on this conception of noise reduction should be continued [Czech M.J., Thomas, R.H., Elkoby, R., 2012].

When adding the sideline and retraction points more than 6,5EPNdB of reduction of jet noise was achieved by mounting a better common nozzle relatively to an isolated nozzle of the baseline. The better common nozzle contains T-fan chevron (Figure 4.33) oriented for longer chevrons in an asymmetric pattern from the airframe and ground observer location and the main chevron, which in essence is a homogeneous structure by circumference. This nozzle was selected and manufactured for the experiment with high accuracy to obtain the aeroacoustic characteristic of N+2A HWB concept in NASA [Czech M.J., Thomas, R.H., Elkoby, R., 2012].

Addition of a common-type pylon gave considerable spectral changes reducing the jet noise up to 4 dB at lower polar angles and increasing it by 2-3 dB at right angles. Moreover, the pylon also had a strong azimuth effect of redistributing to noise sources. Mountings on two diameters of the fan in front of the wing trailing edge provided shielding in the front arc at high frequencies either for axially-symmetric nozzle or for the common round nozzle with pylon. It matches with phased array measurements, which assume that high-

frequency sources are located predominantly near the nozzle outlet and consequently are shielded. Medium and low-frequency sources were observed further by the stream and shielding reduced far less.



Figure 4.33: Chevron nozzle, type T-fan

The engine with *m*=7 ran in peculiar cycle periods at static conditions and in flight conditions. Pylon effect and its orientation for jet noise were also studied as a function of bypass ratio and cycle conditions. Adding of the pylon led to considerable spectral changes reducing jet noise up to 4 dB at high polar angles and increasing it by 2-3 dB at direct angles. In order to estimate noise shielding a model scheme to scale was presented so that the jet nozzle was located from the trailing edge to several diameters before the trailing edge of the airframe model. Mounting on two diameters of the fan in front of the wing trailing edge provided only restricted shielding in the first arc at high frequencies either for axially-symmetric nozzle or for the common round one with a pylon. The pylon was additionally modified as for the technology, which inflates air via pylon flange, which is efficient for reduction of low-frequency noise and moving the jet noise sources closer to the nozzle outlet (Figure 4.34). Further, it is reviewed the concept of the active pylon, where the flow is inflated via the lower part of the thermal flange. Reduction by 1 dB was revealed in mid angles with blow pressure factor. Configuration with a stronger submission of the chevron and pylon oriented opposite to microphones caused the maximum reduction of jet noise. Additionally to the jet noise source the shielding of the wide-band spot noise source was recorded with reduction of the noise level up to 20 dB.

Generally, the following was studied in the work: the effect of noise source position relatively the trailing edge, influence of vertical surfaces, presence of the pylon with blowing of air through holes in the pylon [Czech M.J.,Thomas, R.H., Elkoby, R., 2012].

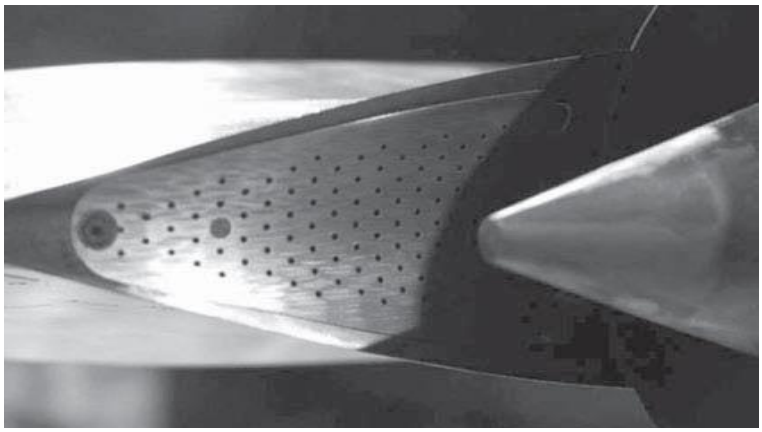


Figure 4.34: Pylon with blowing of gas to the stream

With the reduction in jet noise, fan noise is becoming the dominant source of aircraft noise. Design features of the fan system for minimum noise, include choice in the number of rotating blades and static vanes, the distance between these two rows of blades/vanes, detailed geometries of the rotor blades and stator vanes

(including sweep) and the rotor rotational speed. Key issues are the fan aerodynamic and mechanical performance, stability and stall margin, and the manufacturing complexity and cost. Acoustic liners in the nacelle play a very important role in reducing turbomachinery noise before it escapes from the engine, as the acoustic energy is converted into very small amounts of heat as the sound wave passes over the acoustic liner. Simply extending the length of the nacelle to increase the area available for acoustic liner introduces weight and drag penalties, so there is a need to increase the effective acoustic areas within the existing nacelle length and to enable acoustic liners to be employed reliably in some of the more hostile areas of the engine, bringing significant manufacturing, materials and design technology challenges. Attention to detail is important, and the zero-splice intake liner (which first entered service on the Airbus A380 with the Rolls-Royce Trent 900 engine, see Figure 4.35) has been very effective in reducing fan noise at aircraft departure, far greater than one would expect for a relatively small increase in acoustic liner area. Single-layer and double-layer liners with perforated and mesh facing sheets are standard on aero-engines, but more research is required to understand their acoustic impedance characteristics. The liners need to attenuate simultaneously both low-frequency combustion noise and high-frequency turbine noise. More research is also required in novel liner designs and novel materials for acoustic liners. In order to ensure aero-engine liners are optimised, improved duct propagation prediction models are required, in particular for 3D intakes (including non-linear propagation effects) and for 3D bypass ducts (including propagation through the jet shear layer). There is a trade between penalising the turbine's weight and performance to reduce noise at source against increasing the engine weight and maintainability problems by incorporating acoustic liners in the core duct. A total-system multi-disciplinary-optimisation design approach is required.



Figure 4.35: Industry first 100% acoustic inlet on A380/Trent 900

The industry is committed to reducing aircraft noise even further (Figure 4.36). Aircraft, engine and nacelle manufacturers are investing in extensive research programmes to deliver major additional improvements in the future. These include collaborative Aircraft Noise research programmes, such as SILENCE(R) (£90M) and OPENAIR (£25M) partly funded by the EU and partly by industry, and ANDANTE (£3.3M), SYMPHONY (£5M) and HARMONY (£4M) partly funded by the UK Technology Strategy Board [Sustainable Aviation Noise Road-Map, 2018].

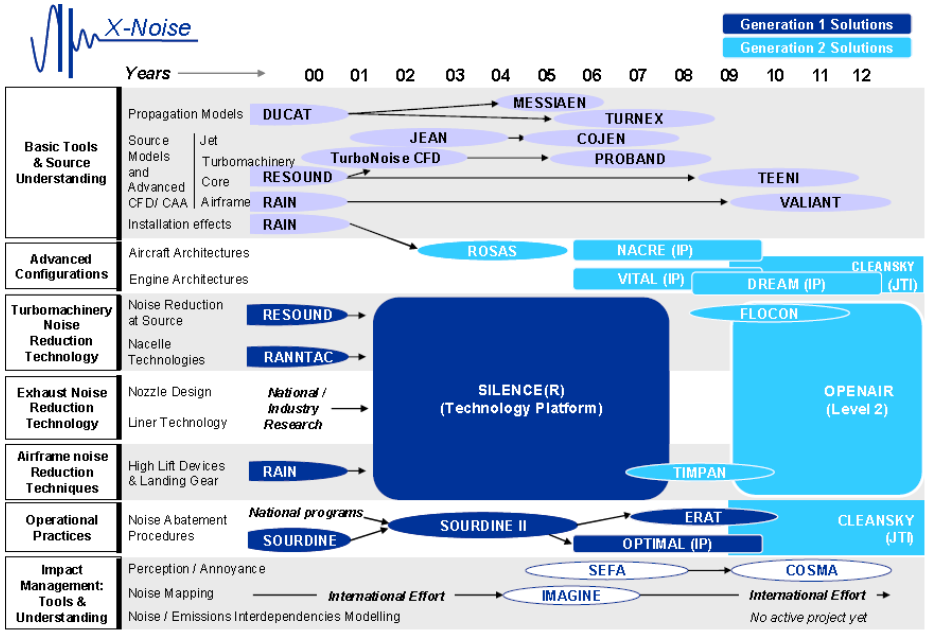


Figure 4.36: Roadmap of EU Aircraft Noise Research Projects vs Key Technical Areas (Generation 1 and 2 solutions - NRT1 and NRT2 performances – were achieved by results of the projects shown and classified in accordance with priority acoustic sources)

In parallel with an evolution largely driven by global environmental issues, there is evidence of increased sensitivity to noise in local communities impacted by aviation operations despite a significant reduction of aircraft source noise over the years. The air transport growth perspectives in Europe are still conditioned by improvements in all three elements of the ICAO Balanced Approach [ICAO Resolution A40-17]. The initial SRA1 approach presiding over the definition the ACARE 2020 noise targets remains valid (Figure 4.37), as originally based on the Balanced Approach concept developed by ICAO:

- The first noise target aims at reducing noise emission of flying vehicles by half, which was translated in quantitative terms as an **average reduction of 10 decibels per operation**, taking into account technology benefits as well as operational improvements.
- The second noise target aims at ensuring that the 10dB benefit in noise emission anticipated for fixed-wing aircraft effectively leads to **no impacted people outside airport boundaries,** provided the appropriate management practices are in place.

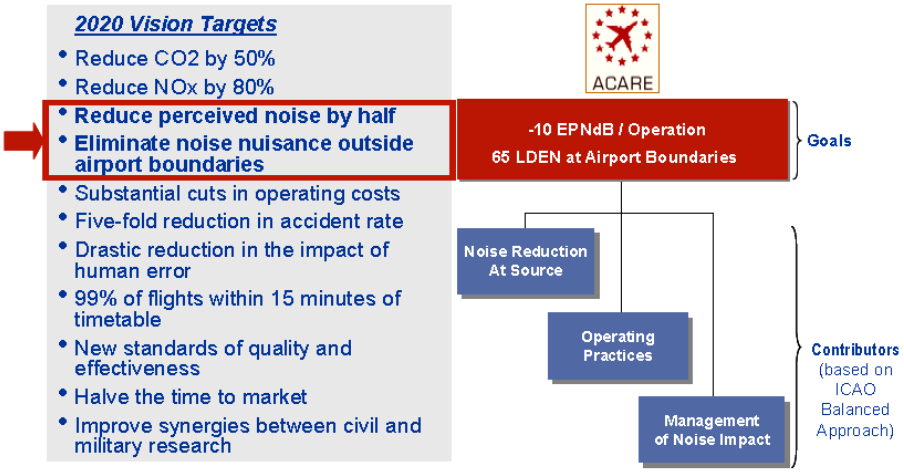


Figure 4.37: ACARE SRA 1: Noise Goals for Fixed-Wing Aircraft

Three years ahead of 2020, the progress registered since 2000 is significant, reaching an excellent level of completion with about 64% of expected benefits secured, due to effective implementation of the research roadmap and associated priorities. In terms of identified ACARE contributors, the investigation and development of recommended ACARE solutions have been well supported at European level over the years, complemented by a steady activity at a national level. The first two elements of the Balanced Approach concept (noise reduction at source, noise abatement procedures) constitute the identified contributors to the 10dB reduction aircraft noise target, and can be further described in terms of associated technical and operational solutions as shown below:

- **Quiet Aircraft contributor** associated solutions**:** Noise Reduction Technologies (NRT) generation 1 and 2, Novel aircraft and engine/power plant architectures
- **Noise Abatement Procedures contributor** associated solutions**:** Improved Operating Practices with Current Concepts / Optimized Operations with New Technology / ATM-ATC Integration

At the occasion of previous progress assessment exercises, a methodology has been established in EU XNoise project (**X-NOISE network** as part of its activity, has identified gaps and priorities, supporting the definition of a general strategy addressing the anticipated 10 dB reduction per operation in a phased approach by means of a significant effort on Technology as well as Noise Abatement Procedures– NAP, Figure 4.38), based:

- On the internationally recognised **Technology Readiness Level scale** (Figure 4.39), that allows keeping track of the situation of individual technologies identified in the SRA1.
- On a dedicated process, called **Technology Evaluator**, involving a predictive model with the capability to roll up the benefits of individual technologies at the solution level and establish the progress achieved globally, including operational aspects.

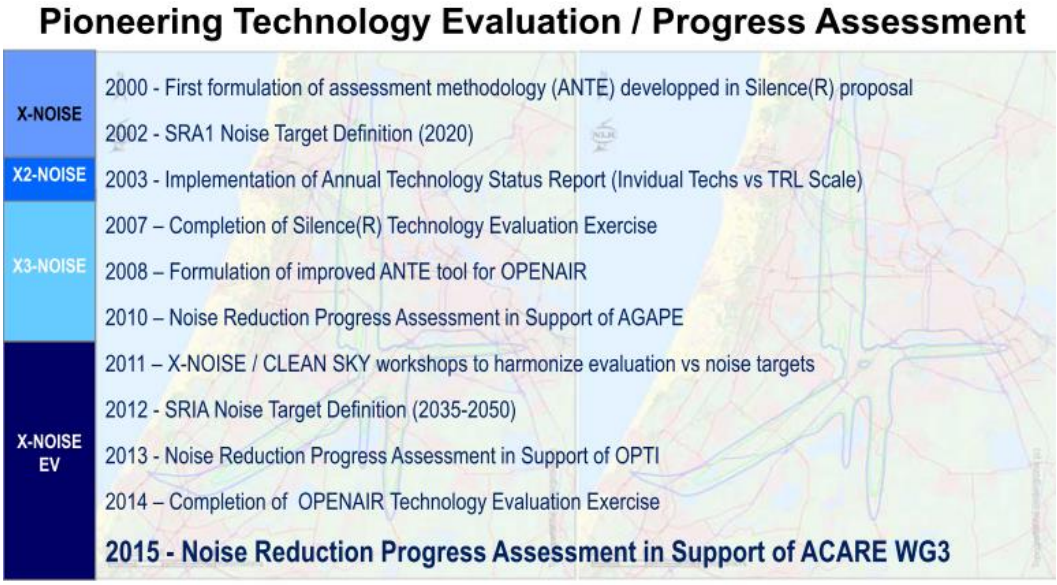


Figure 4.38: XNoise Pioneering Technology Evaluation / Progress Assessment

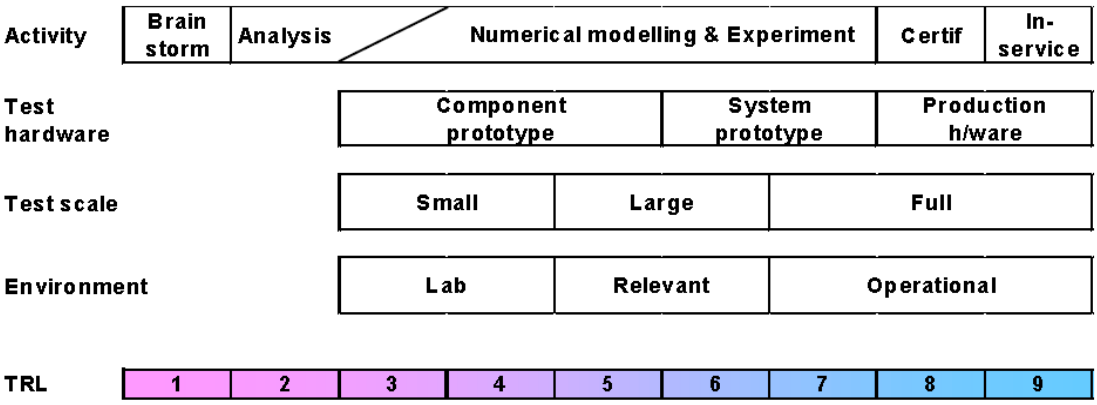


Figure 4.39: Technology Readiness Level Classification used for solutions assessment

An approach by consensus based on expert's judgement, assessment of the TRL situation and results from the technology evaluation exercises have then been used to perform the 2015 progress assessment, coming up with updated progress achievement figures and formulating associated recommendations for future research. Recommended Phased Approach to meet ACARE Noise Goal #1 includes analysis of expected advances on noise reduction with Noise Reduction Technology 1 (NRT1) and NRT2, as well as the NAP (Figure 4.40).

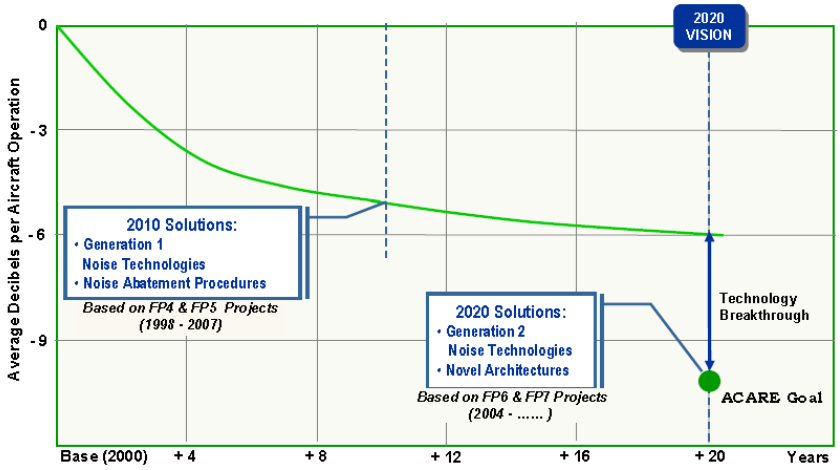


Figure 4.40: Expected advances on noise reduction with NRT1 and NRT2, as well as the Noise Abatement Procedure

Since the year 2000 a number of civil air transport aircraft have been certified by the European industry, a few others, still in their development phase are planned to be certified before 2020. Certification requirements for aircraft noise during these 20 years were changed twice (Figure 4.25) – in 2006 and 2017, once again basing on NRT1 and NRT2 achievements, reached in EU (Figure 4.40). The prime purpose of noise certification is to ensure that the latest available noise reduction technology is incorporated into aircraft design demonstrated by procedures which are relevant to day to day operations, to ensure that noise reduction offered by technology is reflected in reductions around airports. The results of aircraft noise certification provide a representative panel of effective implementation of state of the art NRT1 delivered to TRL6 by completed research programmes such as Silence(R) and Vital (Figure 4.41). The observed average achievement is slightly over the expected 30% of the ACARE target. In dealing with the further steps towards the -10dB target (NRT2, Novel Architectures), the 2015 assessment exercise benefits from the achievements of the OPENAIR project as well as interim results from CLEAN SKY in specific areas related to business jets and regional aircraft in particular.

At the end of the OPENAIR projectNRT2 have achieved TRL 4/5 (look in Figures 4.36 and 4.41) through large scale testing in wind tunnels and dedicated engine fan or exhaust rigs. These technologies have been aimed primarily at short-medium range and long-range aircraft fitted with advanced ducted turbofans. Through CLEAN SKY, additional efforts reached similar TRL achievements on complementary noise reduction solutions aimed at Regional Aircraft (low noise landing gear and high lift devices) and Business Jets (U-Tail). In addition to technology solutions, CLEAN SKY will also bring further consolidation of noise abatement procedures benefits. At last CLEAN SKY has produced a first noise evaluation of the Counter Rotating Open Rotor (CROR) engine concept at mission level on a Short-Medium Range aircraft.

When combining CLEAN SKY interim analysis with the OPENAIR final analysis at airport level and considering the relative importance of business and regional operations, it can be concluded that a typical 2.5 dB additional benefit relative to the 5dB already consolidated at TRL 6 can be expected from NRT2 provided such technologies mature to TRL6 in time for 2020 (Table 4.13).

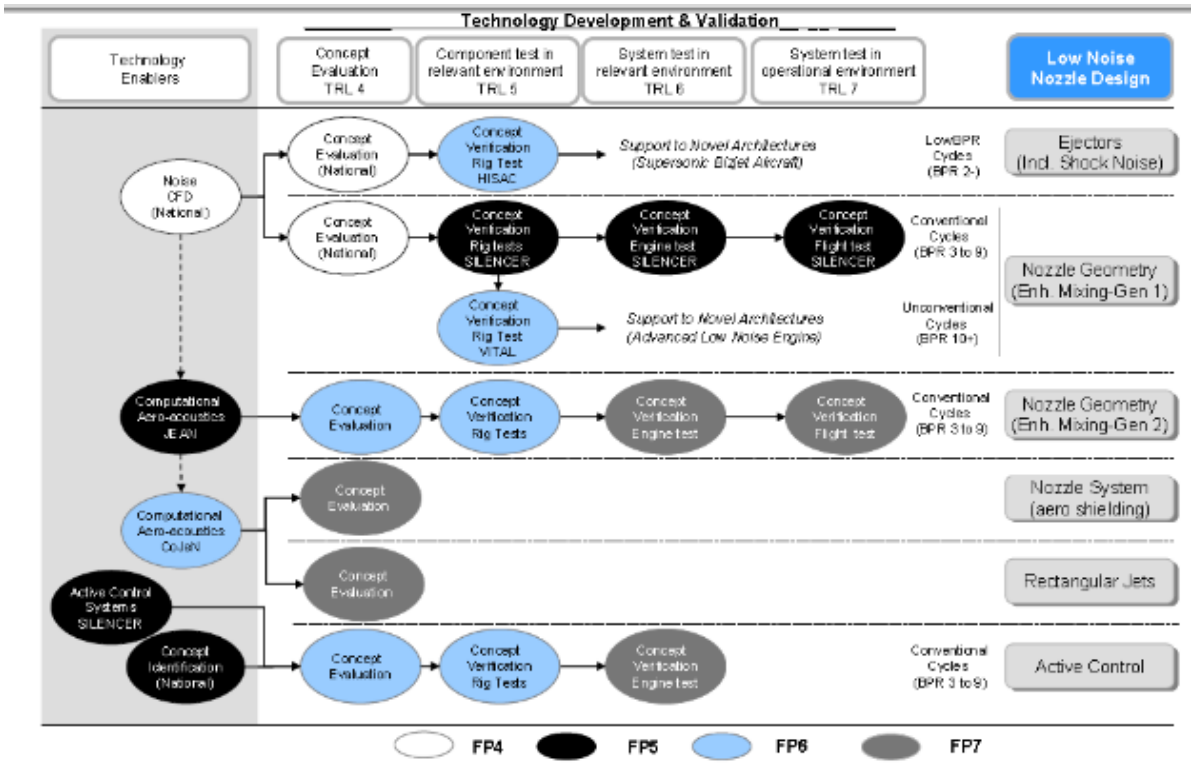


Figure 4.41: Noise Reduction Technologies Development & Validation

Technology or Enabler	Description	Previous projects	On going project	Technology Readiness Level	
				Achieved in 2001	Achieved In 2009
Advanced low noise nacelle concepts	Intake lip liner (BPR7-9)	Silence®		3	5
	Intake lip liner (BPR6)	Silence®		3	5
	Negatively Scarfed Intake (BPR 6)	Ranntac Silence®		4	6
	Negatively Scarfed Intake (BPR7-9)	Silence®		1	6
	Bypass duct lined splitters		Openair	1	3
	Scarfed nozzles		Openair	1	3

Table 4.13: Technology Readiness Level and Technology Status

While such a progress has been registered in terms of secured achievements, the gap to be covered by new programmes has stayed at the level identified in previous assessments. This is due on the one hand to

uncertainties that remain about the capability to support successful OPENAIR technologies to TRL6 through static and flight demonstrations before 2020 and on the other hand to a similar lack of visibility relative to the emergence of ambitious multidisciplinary initiatives dedicated to environmentally friendly advanced aircraft configurations and design. In contrast, similar projects have gained momentum in other parts of the world.

In the paper [Nae, C. 2014] the level of technological readiness of the most promising technologies are assessed, as well as general integration into a new generation of Green Regional Aircraft (GRA), as a highly optimized configuration that meets the requirements for FlighPath 2050. The design features of aircraft for achieving the ACARE goals, i.e. fuel efficiency increase, acoustic emission and CO_2 emissions reduction, are analyzed in the paper [Szodruch, J., et al., 2011]. One of the methods of noise reduction is an electric aircraft with More Electric Aircraft (MEA) technology [Baharozu, E., Soykan, G., Ozerdem, M. B. 2017].

As of the end of May 2018, the leading position in the aircraft engine market for the entire fleet of passenger aircraft in operation was occupied by CFM International (a joint venture between General Electric and Safran, ~44 %) and General Electric (~22 %). In the engine segment for the long-haul narrow-body aircraft, the leaders are CFM International (~71 %, the CFM56 TFE family) and the International Aero Engines (~19 %, the V2500 TFE family).In the engine segment for regional aircraft: General Electric (~72 %, the CF34 TFE family), and Rolls-Royce (~17 %, theAE3007TFEfamily).Intheenginesegmentforwide-body aircraft: General Electric (~51 %, the CF6, GE90, and GEnx TFE families), and Rolls-Royce (28 %, the RB211 and Trent TFE families).

Aircraft companies are currently exploring many different options for upgrading their aircraft, including the possibility of installing several models of next-generation engines. In addition, company specialists are exploring other ways to modernize future aircraft in addition to the use of new power plants(PPs). Among the upgrade options under consideration are the use of a completely new wing and an increase in the height of the chassis racks, which would make it possible to install engines with a high bypass ratio on the aircraft, which could reduce fuelconsumptionby10 %comparedtoexistingmodels. Composite winglets and electronic steering system can also appear on remotorized aircraft.

Let's consider briefly the main directions of new technologies. Rolls-Royce engines have new technologies introduced (Figure 4.26), providing low noise. Figure 4.42 shows the compliance of Rolls-Royce engines with modern ICAO requirements (Chapter 14 of Annex 16, vol. 1).

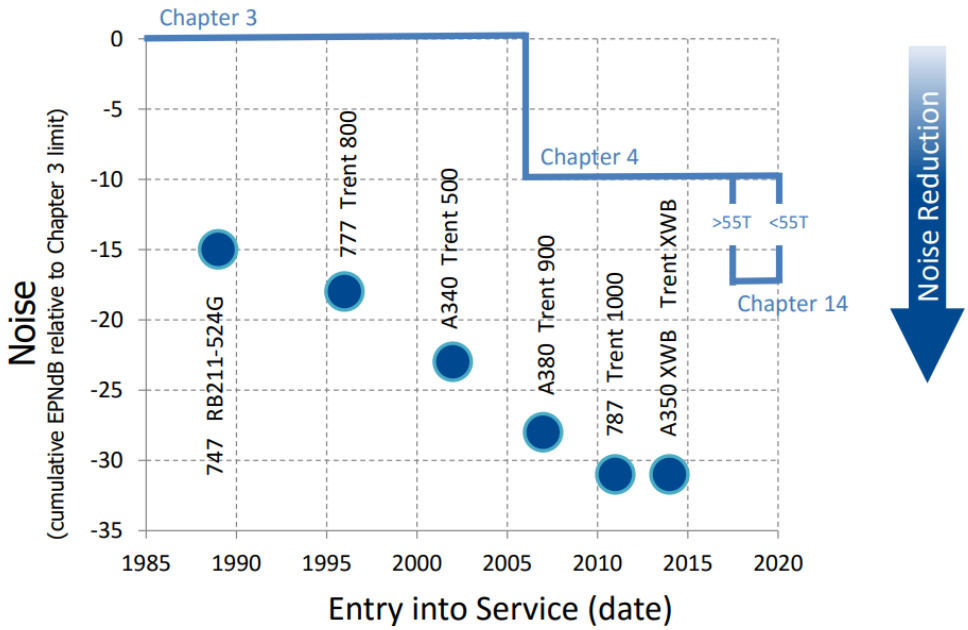


Figure 4.42: The compliance of Rolls-Royce engines with modern ICAO requirements

The noise reduction in Rolls-Royce engines is provided by increasing the by-pass ratio of the engine, reducing the fan noise, optimizing the engine cycle, using the contra-rotating rotors, using the sound-absorbing structures and reducing the level of turbulence in the inlet section. Reduction of fan noise is provided by the use of a low-speed advanced fan (reduction of the dipole acoustic noise source). Wide-chord fan blades have a twist in height and are made of composite materials. Reduction of the acoustic interaction between the fan impeller and the outlet guide vanes is provided by inclined and specially profiled blades, the number of which is selected to provide the "cut-off" effect. The development of optimized Outlet Guide Vane (OGV) made it possible to significantly reduce discrete and broadband noise (Figure 4.43-4.45 present a set of technologies in the Rolls Royce engine to reduce noise).

To achieve this goal, a multidisciplinary aerodynamic and acoustic optimization of the fan OGV design was performed, a reduction in the number of vanes from 42 pieces to 14 pieces was considered [Kröger, G., Schnell, R., Humphreys, N. D. 2012]. In addition, the design of the inner surface of the casing is made without seams, which are one of the sources of the quadrupole acoustic source of noise at the inlet and outlet of the fan.

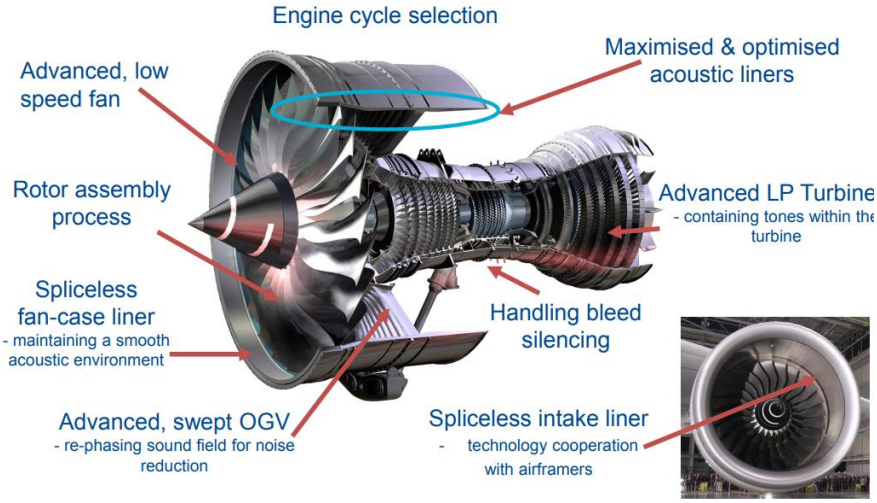


Figure 4.43: Rolls Royce engine noise reduction technologies

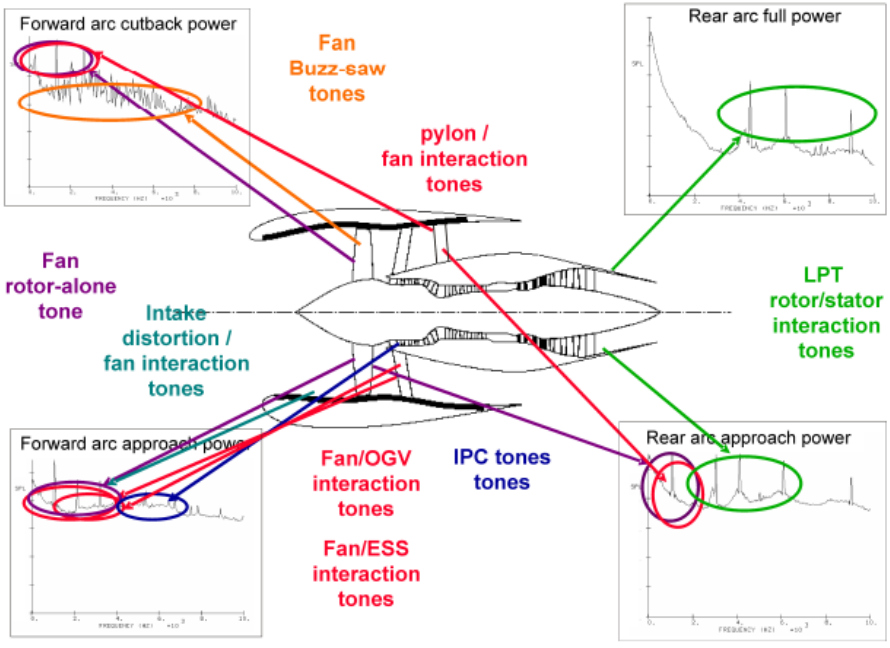


Figure 4.44: Engine discrete noise sources and their reduction [Crighton D., 2007]

Using an inlet section of a special design contributes to the reduction of the turbulence level at the engine inlet, which in turn reduces the level of vortex noise at the fan inlet. Also, acoustic emission reduction is achieved by using sound-absorbing materials and reducing the tonal noise of a low-pressure turbine. A decrease in tonal noise is provided by improved aerodynamics of the turbine blades and a decrease in the rotational frequency.

To achieve ACARE noise reduction goals, Rolls Royce is developing engines under the Advance and UltraFan programs, which are planned to be completed in 2020 and 2025, respectively. These engines feature the following:

- A three-shaft modular design of a high-bypass engine (for Advance up to m=11, for UltraFan up to m=15);
- Improved aerodynamics of the impeller machines and a high-pressure ratio up to 60 for Advance and 70 for UltraFan;
- Multiparametric optimization of aerodynamic and acoustic characteristics, use of the "Intelligent Engine" concept;
- Application of 3D printing technology.

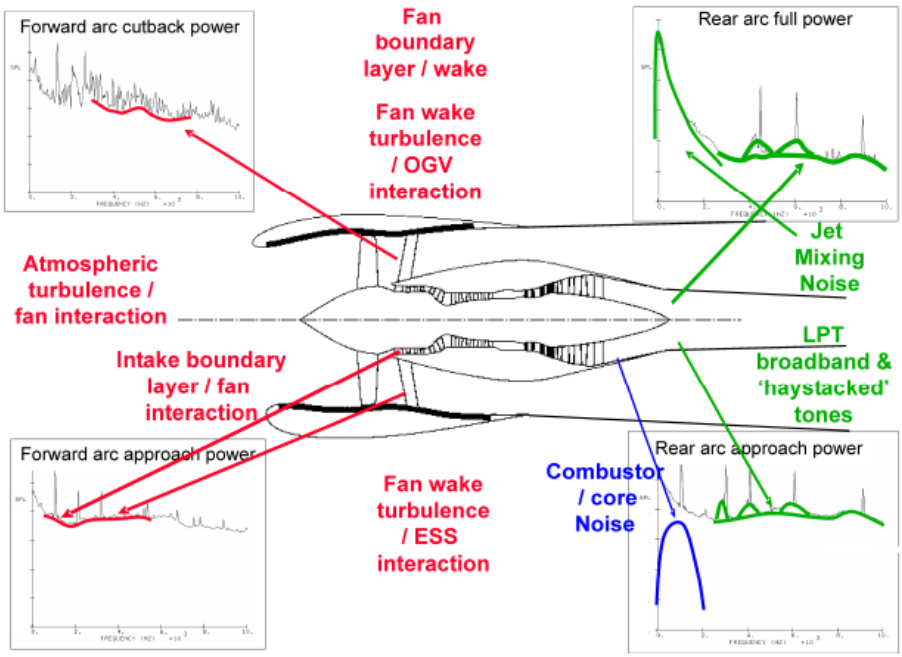


Figure 4.45: Engine broadband noise sources and their reduction [Crighton D., 2007]

The proposed measures allow to reduce engine weight and increase fuel efficiency by 20% for Advance and 25% for UltraFan, as well as to reduce noise level and harmful emissions level (Innovation through evolution, 2019).

The Advance configuration will be the baseline for the next-generation UltraFan engine. The Advance project will become the implementation of a whole range of new technologies, and, first of all, it is aimed at increasing the thermodynamic efficiency of engines.

The UltraFan program will implement all innovations of Advance and with the use of gear technology will be aimed at increasing thrust efficiency.

The large-scale use of composite materials provides the most significant contribution to the reduction of the total weight of the power plant. Composite fan made of the third-generation carbonic titanium became advanced. Composite materials will also be used in the manufacture of the fan casing, the radial drive shaft, the rear housing and the attachment points for additional equipment. Among other upgraded components of Advance engines are turbine blades made of titanium aluminide.

Among other features of power plants are dynamic seals, hybrid ceramic bearings, enhanced adaptive systems, three-dimensional aerodynamic blades of the fifth-generation turbine, hydraulic switches for efficient air-cooling control. The new engines will also use the next-generation combustion chamber and ceramic matrix composites.

The fan speed reduction in the UltraFan engine will be ensured by the use of a special reduction gear. The technology of a geared fan drive is quite an attractive solution to the problem of weight reduction. The gearbox application will reduce the fan speed, which is beneficial for noise reduction when the fan rotates. The composite materials application will reduce the weight of the fan blades. In addition, to improve the aerodynamics of the blades, it is suggested to use the boundary layer control [Whurr J., 2013].

To maintain stable operation of a larger diameter fan, Rolls-Royce engineers are considering the possibility of using a variable area nozzle. The design of the UltraFan includes the blisk stages of the compressor (Figure 4.46). In addition, the design of the nacelle will allow reducing the aerodynamic drag. Further strategic development of the Rolls-Royce company will be based on Open-Rotor engine technologies.

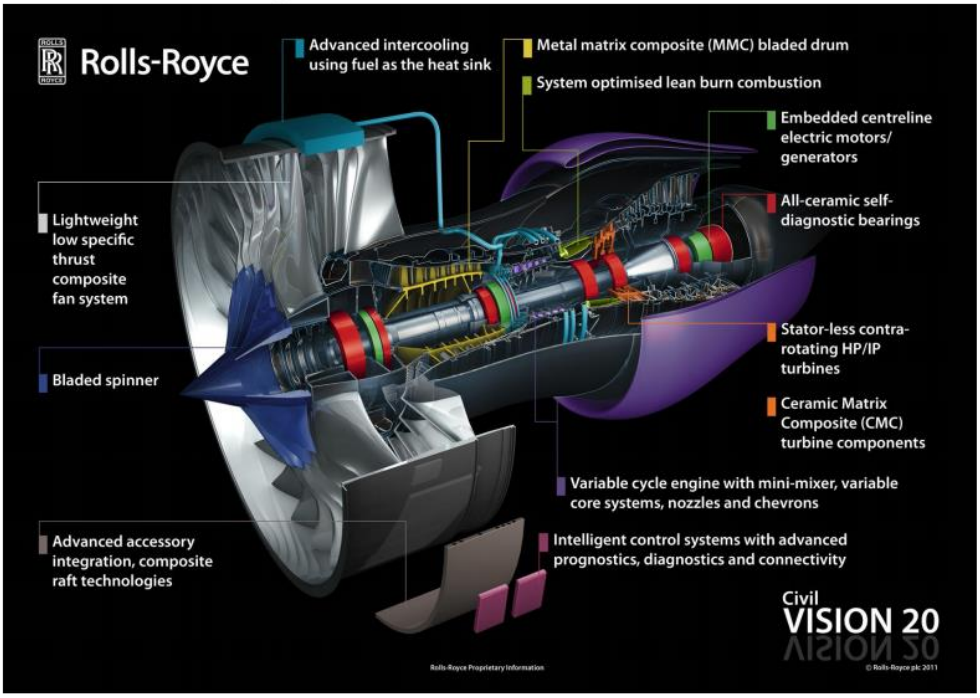


Figure 4.46: Rolls Royce technology for the future engine

SAFRAN engineering solutions for many years have followed their commitment to improving the environmental and economic parameters of their products, including some well-known innovations in this field. For example, the CFM56 engine (designed and manufactured by CFM International, a joint venture of Snecma (Safran) and General Electric with a 50/50 share of equity) today is, from a fuel efficiency point of view, one of the most efficient engines in its class.

Its successor, the LEAP engine, will reduce fuel consumption by 15% relative to CFM-56-5B, which in its turn will reduce harmful emissions. Also, a number of engineering solutions for significant improvement of acoustic characteristics are introduced in this engine.

The structure of the engine is based on proven principles. For example, the engine design does not include a gear for speed reduction, which significantly complicates the engine design. One of the most striking engineering solutions is the design of fan blades made of a three-dimensional woven composite.

The LEAP engine also involves the integration of the power plant with Airbus A320neo, Boeing B737MAX and Comac C919 to reduce acoustic impacts. Lots of innovations are used in the fan, including three-dimensional woven composite blades, which have already been successfully tested on the Mascot engine demonstrator. The patented technology is based on resin transfer moulding (RTM). Within the framework of this technology, liquid resin is introduced between the matrix and the solid opposite matrix, that ensures the production of lightweight but strong cast parts of three-dimensional woven composites using a process that is easy to implement on an industrial scale.

The acoustic characteristics of the fan are reduced by the optimized shape of the blades, the absence of shroud platforms and the reduction in the fan blade weight. The engine nacelle is made of special composites, which reduce the noise level.

Currently, SAFRAN is working on a future technological breakthrough - the next-generation engine based on the "Open-Rotor" concept. The first demonstrator of this engine - GE36 - was developed back in the 80s of the last century jointly by Snecma (now part of the SAFRAN group) and GE. Offering an ultra-high bypass ratio (UHBR), this type of engine, while providing the same speed as traditional by-pass engines, provides a fuel flow rate by an average of 25% less compared to existing turbofan engines and 10% less compared to advanced turbofan engines.

The application of the "Open-Rotor" design will entail significant changes in the nacelle design since in this case, it will play an even greater role in the reduction of noise. The development of the nacelle is performed by AIRCELLE, a member of the SAFRAN group. In the manufacture of nacelles, honeycomb materials are used, which helps to reduce the noise level of the engines. Many other improvements are introduced at every stage of the product life cycle, reflecting the SAFRAN approach to environmental design. A nacelle is a complex system located at the intersection of the competence areas of engine manufacturers and airframers. AIRCELLE develops titanium nozzles to improve engine performance and reduce noise [Beple, M. 2015].

SAFRAN environmental approach focuses on five key areas: economic risks, energy consumption, the increasing shortage of natural non-renewable resources, atmospheric emissions and noise. SAFRAN is one of the active participants in the European research program Clean Sky. In particular, SAFRAN is researching the field of next-generation helicopters and open-rotor aircraft engines. The open-rotor engines can be commissioned by 2030 and reduce fuel flow rate by up to 25%.

One of the innovative products, "Development of wireless communication and the Internet", has played a decisive role, as the data collection from on-board systems became almost automatic. By analyzing the collected data, SAFRAN can offer recommendations for reducing the fuel flow rate and CO_2 emissions during the flight or changing the flight path to reduce the noise level on the ground.

Pratt & Whitney engineering solutions ensure the reduction of the fuel flow rate, noise and emissions level by developing the PurePower engine family (maximum thrust of 10,000-40,000 pounds). It allows optimizing the routes, reduce flight time and save on environmental fees. Thus, costs and environmental pollution are reduced.

The PurePower PW1000G engine allows optimizing the combustion process by more than 16% compared to the best modern engines - from regional jets to narrow-body long-range aircraft.

The TALON ™ X Pratt & Whitney fuel combustion system dramatically reduces the level of pollution produced. The PW1000G engine exceeds the requirements of the most demanding standards (CAEP/6) for nitrogen oxides (NO_x) emissions by 50%.

The PurePower PW1000G engine will allow reducing carbon emissions by 3000 tons per aircraft per year. The technology has successfully passed the tests using alternative fuel. Thus, according to the company's plans, this engine will be able to remain in operation in the long term for most of the 21st century.

The PurePower PW1000G engine provides a 50% - 75% reduction in noise level. The noise level value is 15-20 dB below the most stringent of existing standards (ICAO Stage 4).

The fan noise in the PurePower PW1000G engine is reduced by using a fan drive system. This allows rotating the engine fan at a slower speed when compared with the low-pressure compressor and turbine while increasing the by-pass ratio. This technology provides a lower fuel flow rate and a lower level of pollution and noise produced. The PurePower PW1000G engine is optimized for a new-generation aircraft and allows to provide the highest levels of green operation and fuel efficiency with lower ownership costs during the engine life cycle.

The engineering solutions of Pratt&Wittney Canada are implemented on turbofan engines PW300, PW500, PW600 and PW800. The engines are equipped with the latest advanced technologies in terms of performance, reliability, durability, fuel flow rate and environmental friendliness.

The low noise level is provided by an improved wide-chord fan with the use of shock wave control and by a highly efficient jet nozzle with acoustic optimization.

GE Aviation annually invests more than 1 billion USD in research and development in the aircraft engine industry.The optimized design of the GEnx engine fan blades and the use of composite materials allow reducing the acoustic emission of the fan. The new GE9X engine is at the R&D stage, including component testing.The new-generation PASSPORT engine with improved environmental and economic performance is developed for the new Bombardier business aircraft Global 7000 and Global 8000.

In Russia, CIAM and TsAGI are involved in reducing the acoustic emission of engines. CIAM develops and conducts experimental studies of typical high-load, high-efficiency axial stages of fans, low pressure and high-pressure compressors of advanced gas turbine engines in a wide range of stages parameters variation. Measures are being developed to ensure the parameters of the stages and multi-stage compressors by using stationary cascades and other controls in the areas of unstable flow. CIAM is working on the improvement of design flow models in the RANS, URANS approximation in direct and reverse setting, including taking into account the nonstationary interaction of the blade rows, by the NLH method, both for gas dynamics problems and for aeroacoustics problems.Effectiveness of advanced technologies to reduce fan noise is verified on model fans, whose diameter is 400-700 mm. TsAGI specialists have experience in aeroacoustic calculations on high-performance multiprocessor complexes

In Ukraine the scientific and methodical apparatus has been improved in terms of determining the dependence of the parametric appearance of the PP engine on the characteristics of the aircraft airframe. In this case, several structural-layout solutions of the airframe and engines within the PP have been created [Shmyrov V., Merkulov V., Loginov V., 2020]. Refinements of the boundaries for expanding the range of application of experimental data in the analogy method has been made. Experimental studies involved flight data on the family of the An-158-type aircraft (Figure 4.47), designed by Antonov State Enterprise, equipped with different engines in its power planr (PP). The construction of a cargo-range diagram for the An-158 aircraft, and the feasibility study of engine replacement within the PP, would show the advantages and disadvantages of aircraft remotorization.

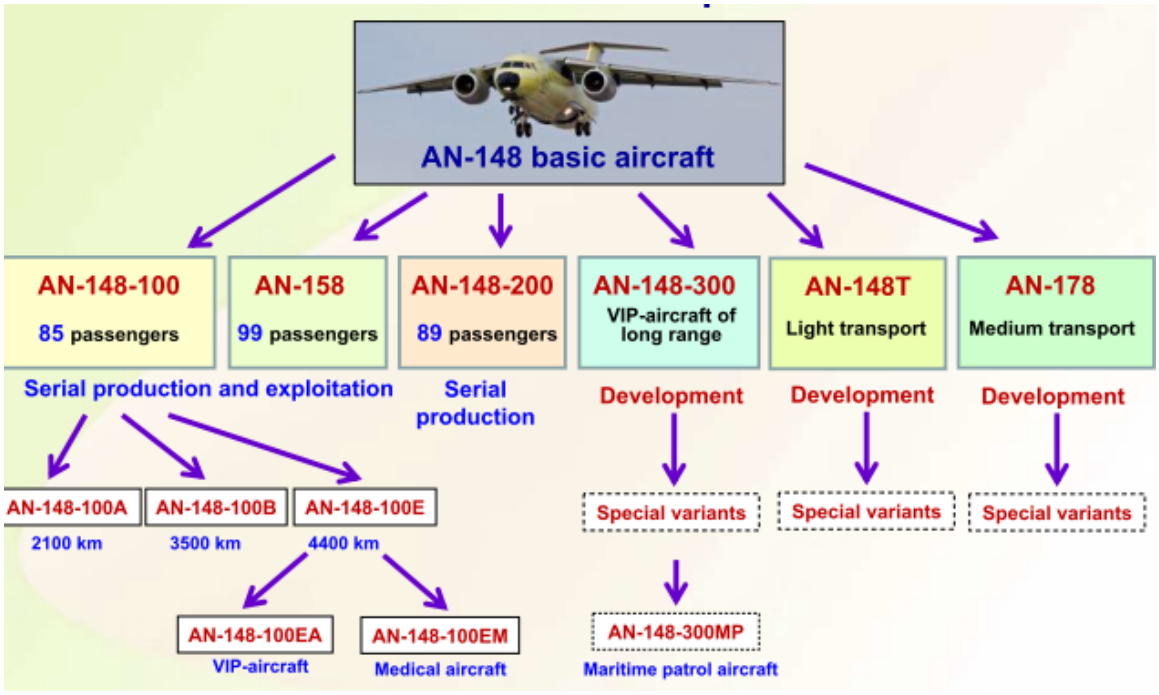


Figure 4.47: Family of the AN-148 passenger regional aircraft and the AN-178 medium transport aircraft

In order to meet the requirements to improve the AC fuel efficiency, economic performance, and competitiveness, a single D-436-148FM engine is planned for the entire family of the Antonov aircraft (An-148, An-158, An-178). Based on our investigation of the performance of the engine and the An-158 aircraft, a feasibility study has been carried out to replace the D-436-148D engine with the D-436-148FM as part of the aircraft's PP. The use of a single engine D-436-148FM for the family of AN-1X8 aircraft shows a clear advantage of such modernization. The data obtained demonstrate that, based on placing a single engine D-436-148FM in the PP system of aircraft the type of An-158, it becomes possible to create a competitive family of aircraft of a given type. Such activities could be proposed for practical implementation at the Antonov Company State Enterprise. Noise requirements – in compliance with requirements of Chapter 4 (with reserve up to ~11 dB cumulative, so ~4 EPNdB – to Chapter 14 [http://noisedb.stac.aviation-civile.gouv.fr/find.php]) International Standard "Environmental Protection", Annex 16 to the Chicago Convention on International Civil Aviation (Volume I «Aircraft noise») and AP-36 Aviation Regulations.

In conclusion, relative to the ACARE noise target of -10dB per operation, the aircraft noise research effort can be considered as globally on track to meet its objective but will require significant support in the few years remaining before 2020. Actions critical to the ultimate success of the global approach initiated around 2000 can be summarized through the following recommendations:

- Bring the most promising NRT2 solutions put forward by the OPENAIR project to TRL6, through an appropriate full-scale validation effort across the board (engines, nacelles, landing gears, airframes).
- Drastically increase the effort dedicated to Low Noise Aircraft configurations noting that while programme prospects are good concerning novel engines architectures, the effort on aircraft configurations is lagging behind.
- Take advantage of the sustained effort on low noise operational procedures to consolidate wider implementation capability.

Aircraft incorporating 'Imminent' Generation 1 technology with significant fuel burn (Table 4.6) and noise benefits are already entering service or are currently offered for sale to the market (including all-new aircraft as well as re-engined aircraft). These are aircraft whose noise characteristics are well-defined. Their impact on noise emissions from EU aviation over the next two to three decades will be substantial.

We consider four distinct categories of 'Imminent' or 'Generation 1' aircraft, namely Regional Jets, Single-Aisle aircraft, Twin-Aisle aircraft and Very-Large Aircraft. Within these categories, we do not distinguish between Generation 1 aircraft produced by different manufacturers, but we do sometimes distinguish between light, medium and heavyweight versions:

Regional Jets (RJ)

In the small RJ sub-division of this category, there is no clear evidence when a new generation of aircraft will be developed; a later date of 2025 has therefore been assumed for the introduction of Generation 1 aircraft, though it should be noted that for regional and large airports the EU aviation noise output depends little on small aircraft in this category.

In the large RJ sub-division of this category, the Bombardier 'C' series is scheduled to enter service in 2014 and the Mitsubishi MRJ in 2015, whilst Embraer are currently evaluating options to re-engine the aircraft due to enter service in 2018.

Single-Aisle (SA)

We divide this category into small, medium and large family members (e.g. A318/9, A320 and A321). The Airbus A320neo family will enter service in 2015 and the Boeing 737 MAX family will enter service in 2017.

Twin-Aisle (TA)

In the small TA sub-division of this category, the Boeing 787 entered service in 2011. In the medium TA sub-division of this category, the A350 XWB-800/900 entered service in 2014. In the large TA sub-division of this category, the A350 XWB-1000 entered service in 2019, and Boeing is currently evaluating a replacement for the B777 to enter service at the end of the decade.

Very-Large Aircraft (VLA)

We do not sub-divide this category, since the noise levels of the Generation 1 aircraft (A380 and B747-8) are broadly similar and the breakdown of future sales into different sizes is less clear. The Airbus A380 entered service in 2007 and the Boeing 747-8 Intercontinental entered service in 2012.

These are aircraft whose noise characteristics are well-defined. A number of these 'Imminent' aircraft have already been certificated. Table 4.14 and Figure 4.48 compare their noise levels with the levels of the aircraft they are replacing for two cases, where the improvement are shown in the average certificated margin to Chapter 3 as recorded on the EASA database to characterise their noise improvement [Aircraft Technology Roadmap to 2050, 2018]. Their impact on noise emissions from EU aviation over the next two to three decades will be substantial.

Current Aircraft	Bypass Ratio	Arrival Noise	Departure Noise[21]	'Imminent' Aircraft	Bypass Ratio	Arrival Noise	Departure Noise
B767	4-5	-4.8dB	-5dB	B787	9-11	-5.8dB	-10.4dB
B747-400	4-5	-1.9dB	-5.9dB	B747-8	9-10	-4.5dB	-11.2dB

Table 4.14: Noise of Current and 'Imminent' aircraft relative to Chapter 3

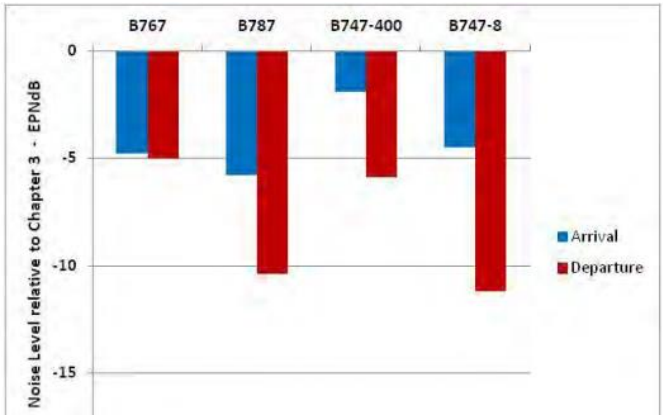


Figure 4.48: Noise of Current and 'Imminent' aircraft relative to Chapter 3

Noise characteristics of new Generation 1 aircraft (Data provided by Airbus [Sustainable Aviation Progress Report 2015-2017]):

- The design noise footprint of the A320neo (68.3t) is nearly a square kilometre smaller than older A320-214 aircraft (68t), Figure 4.49a.
- The Boeing 737 MAX noise footprint is more than 1.7 square kilometres smaller than the 737 NextGen (737 MAX 8 with LEAP-1B compared to 737-800 with CFM56-7B).
- The A350-900 (252t) noise footprint is to be over 2.5 square kilometres smaller than the A340-300 (258t).
- The Boeing 787-8 with Trent1000 noise footprint is more than 2.4 square kilometres smaller than the aircraft it replaces - 767-300ER with CF6-80C2, Figure 4.49b.



Figure 4.49: Noise footprint for of new Generation 1 aircraft: a) A320neo; b) Boeing 787-8

Continuous improvement in aircraft noise performance has occurred over time across various weight categories. Work during the ICAO CAEP work programme from 2010 to 2013 included a review of noise technology goals by independent experts (IE) for the intermediate (2020) and long-term (2030) timescales [X-NOISE, 2015]. The goals indicated in Table 4.15 for 2020 and 2030 provide a reference for potential future developments and are combined with existing aircraft data for the same weight categories (namely Regional Jets **RJ**, Short/Medium Range two-engine aircraft **SMR2**, Long Range two-engine aircraft **LR2** and Long Range four-engine aircraft **LR4**) over the period 1960 to 2015. Figures 4.50 and 4.51 shows the US and EU "technology only" goals harmonized to TRL6 and a common metric. Their respective baselines and noise reduction target versus US and European research goals are also Table 4.15: CAEP IEP2 Aircraft Noise Goals for short-medium (2020) and long (2030) term [Astley R. J., 2014] identified.

Aircraft type	Reference		Mid Term Goal (2020) TRL6			Long term goal (2030) TRL6		
	cumulative margin (EPNdB) v chapter 4	Bypass ratio	cumulative margin (EPNdB) v chapter 4	reduction EPNdB: Total (BPR,NRT)	Bypass ratio	cumulative margin (EPNdB) v chapter 4	reduction EPNdB: Total (BPR,NRT)	Bypass ratio
Regional jet	4	5.0	14	10.0 (6.0 ,4.0)	7 ± 1	21.5±4.0	17.5 (12.0, 5.5)	9 ± 1
Small-medium range (turbofan)	5	5.0	22.5	17.5(12.0, 5.5)	9 ± 1	30.0 ±4.0	25.0(18.0 , 7.0)	13 ± 1
Small-medium range (CROR)	5	–	–	–	–	7.5 → 15.5	8.5	–
Long range twin (Turbofan)	6	6.0	22	16.0 (10.5, 5.5)	10 ± 1	28.0 ±4.0	22.0 (15.0, 7.0)	13 ± 1
Long range quad (Turbofan)	5	5.0	22.5	17.5 (12.0, 5.5)	9 ± 1	27.0 ±4.0	22.0 (15.0, 7.0)	11 ± 1

Table 4.15: CAEP IEP2 Aircraft Noise Goals for short-medium (2020) and long (2030) term [Astley R. J., 2014]

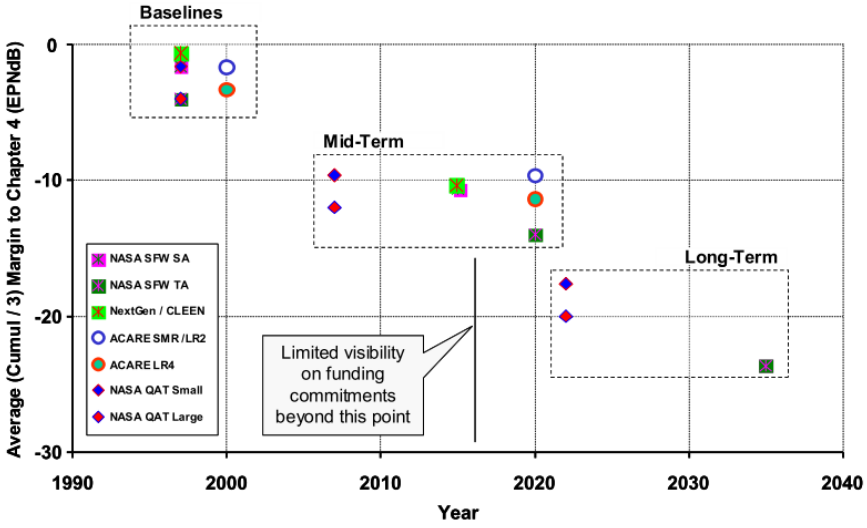


Figure 4.50: Comparison of US and EU research goals [X-NOISE, 2015]

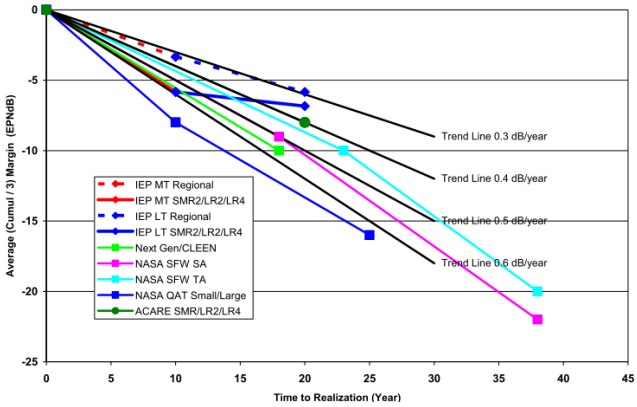


Figure 4.51: IEP2 predicted noise reduction target versus the US and European research goals [X-NOISE, 2015]

Relative to the second ACARE 2020 noise target (no people impacted outside airport boundaries), a pilot study led to the following observations:

- Benefits of each element differ significantly (very airport dependent);
- The effect of Land Use Planning may be of the same order of magnitude as that of noise reduction at source;
- A combination of actions is required to maintain future population affected below 2000 levels.

The full assessment process, however, will require a very significant amount of input data and need effective support if it is to be in place and validated ahead of the next assessment exercise. In the meantime, dedicated research actions should address the development of updated dose-response relationships to allow a translation from exposure (L_{DEN}) to annoyance fitted to the characteristics of today's and tomorrow's operations.

'Future' Aircraft (Generation 2 Aircraft)

The technology and knowledge in both airframe and engine design to achieve these noise goals is yet to be acquired, so manufacturers are engaged in extensive noise research programmes with financial support from the government. An assessment of the noise reduction potential of the *'Future' Generation 2* aircraft in each of the four categories (Table 4.6) is derived with reference to the corresponding Generation 1 aircraft, and is driven by three factors:

- the entry into service (EIS) date of the Generation 2 aircraft type relative to its Generation 1 predecessor (Figure 4.52);
- the rate of underlying annual improvement in aircraft and engine noise levels through evolutionary developments in technology;
- any significant technologies or configurational changes which result in a step-change in aircraft noise (Table 4.1).

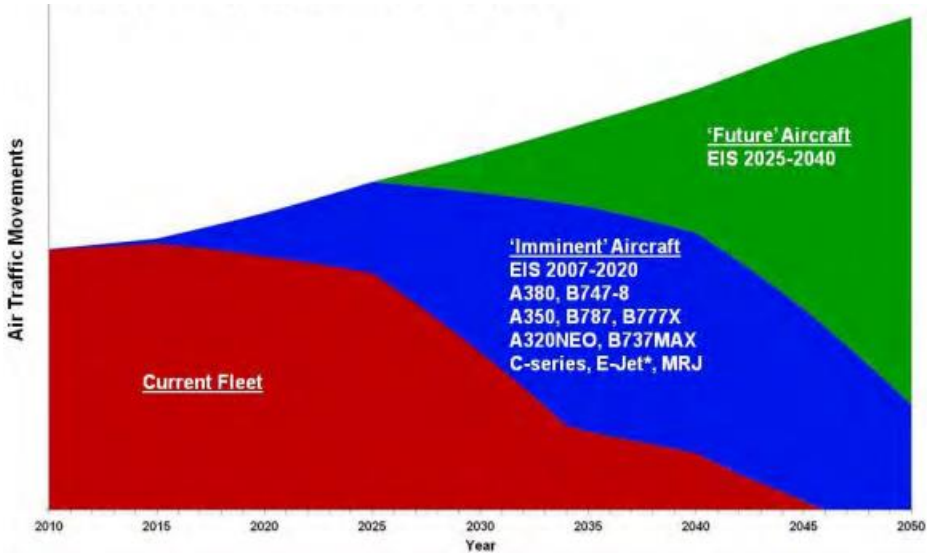


Figure 4.52: Typical fleet transition from current aircraft to 'Imminent' and 'Future' aircraft

At this stage, it should also be pointed out that in noise reduction the main expectations are based on benefits associated with ducted turbofans engine concepts. In parallel, Counter Rotating Open Rotor (CROR) engine concepts have re-emerged in recent years as a serious option to provide the needed fuel burn benefits implied by the targets set for aviation CO_2 emissions reduction, noise was considered as a major issue in the initial investigation effort of such engine concept which culminated in a series of noise evaluation flight tests performed in the US in 1986-1987. As a consequence, a significant research effort has been and still is dedicated to noise reduction of CROR engine concepts (Figure 4.53). At this stage, based on results from model tests in an anechoic wind tunnel (TRL 4), CROR powered aircraft with an EIS between 2025 and 2030 can be expected to produce noise levels similar to those of turbofan-powered aircraft currently under development. When placed in perspective with the best expectations resulting from the 1987 post-flight test assessment, this represents a typical 20dB noise reduction on a cumulative basis, a spectacular achievement for the European research effort initiated in 2008. To consolidate such advances, the effort must be maintained through dedicated research aimed at rotor blade aeroacoustics design, engine/airframe installation (Figure 4.54) and flow control techniques in particular. It is generally assumed that though 2020

objectives will be reached through enforcing new NAP in addition to NRTs, 2050 objectives will require a breakthrough in aircraft architectures.

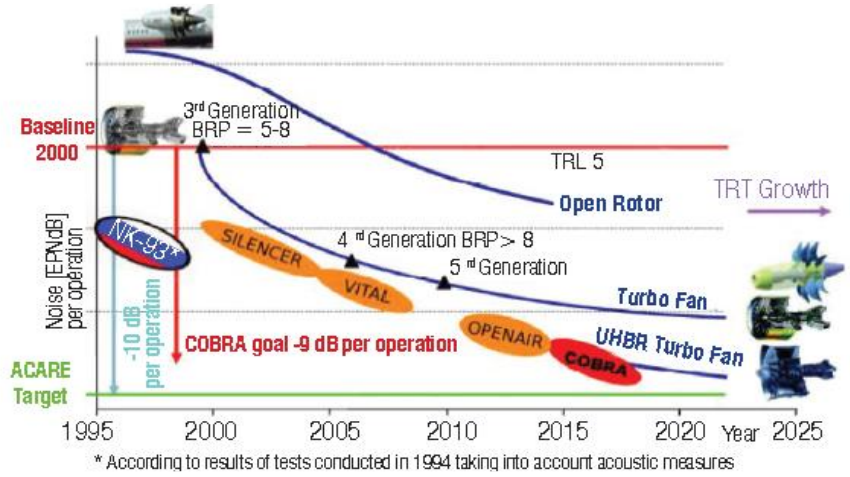


Figure 4.53: Programme Level & EPNL reduction for aircraft noise due to technology improvements



Figure 4.54: Airbus views on a futuristic design for 2030 - future noise reduction technologies with contribution of engine/airframe installation effects

As it was said earlier, one of the advanced developments is an open-rotor engine (Open Rotor), such engines have high efficiency. However, acoustic characteristics require additional research and improvement.In the paper [Perullo, Ch.A., Tai, J.C.M., Mavris, D.N. 2013] the characteristics of an open-rotor engine are analyzed for different operating conditions. Figure 4.55 shows a comparison of the engines.The calculation of the characteristics of an open-rotor engine is presented in the paper [Hendricks, E.S., Tong, M.T. 2012]. It is shown that the designed engine will have higher efficiency. It is also noted that such engines have a margin of 13 dB according to ICAO Chapter 4 requirements or 6 to Chapter 14. To improve the acoustic characteristics of an open rotor, reliable methods of noise calculation are needed.

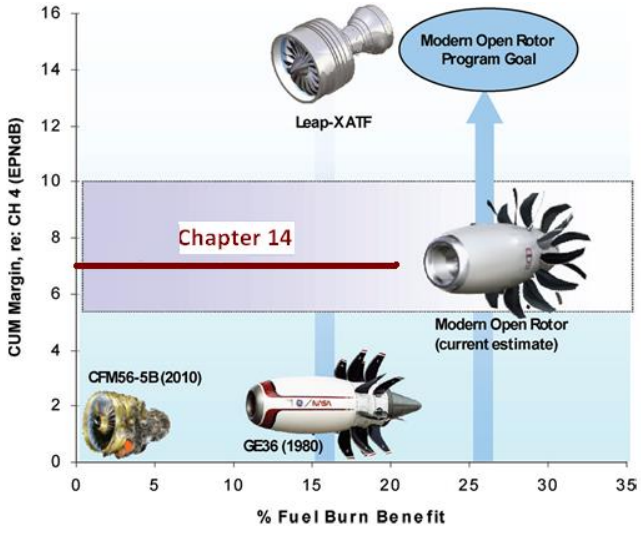


Figure 4.55: Advantages of an open-rotor engine

A number of papers [Hildebrandt, T., Thiel, P., Albert, S., Vilmin, S. 2014; Zamtforth, B.S. 2012; Zante, D.E., Envia, E. 2014] are devoted to the study of the acoustic characteristics of an open rotor. In terms of design, an open rotor consists of two rotor wheels, which rotate in different directions. The results of the paper [Zamtforth, B.S. 2012] showed that in the engine noise spectrum, in addition to the traditional noise components, tonal noise peaks at combination frequencies in the low-frequency part of the spectrum are added. This creates significant difficulties in reducing the aircraft noise with such engines afield.

In the paper [Hildebrandt, T., Thiel, P., Albert, S., Vilmin, S. 2014] the study was carried out with the help of a numerical experiment using NLH (Non-Linear Harmonic method). The first blade ring consisted of 9 blades, the second consisted of 12, the tip radius was 2.5 m, the hub radius 0.75 m, the rotational speed of the first blade ring was 783.6 rpm, the rotational speed of the second - 763.8 rpm. The results of the paper made it possible to investigate the mechanism of generation of the open rotor acoustic emission. The results of the paper [Zante, D.E., Envia, E. 2014] show that for the reduction of acoustic emission, it is necessary to reduce the wake behind the first rotor and to reduce the acoustic effect from the vortices behind the second rotor, which separates from the blade tips.

The paper [Sgadlev, V.V. 2009] presents the results of the blades number optimization for the stage of one of the contra-rotation fans, developed under the European program VITAL. In addition, the paper presents a method for evaluating the acoustic characteristics of a fan. The method is based on obtaining analytical solutions of the Tyler-Sofrin theory and the theory of disturbance propagation in a duct. A program has been developed to obtain these solutions and to present them in a user-friendly form. After optimizing the number of blades of the contra-rotation fan stage, the number of modes decreased by 38.5%, which implies a corresponding reduction in noise levels. This technique will be more efficient if it incorporates the weight coefficients of the mode for better consideration of the human hearing physiology and more optimal adjustment of the sound-absorbing structures (SAS) characteristics.

The results of the paper [Danner, F., Kendall-Torry, C. 2014] showed that when the diameter of the second wheel of an open rotor is reduced by 20%, acoustic emission from the interaction between the first and second rotor wheels are reduced. The jet stream is one of the main sources of the jet engine noise, therefore, research on reducing the jet stream noise is still of vital importance. In the medium term, a method of reducing the jet noise for the engines with m=7...9 is the use of a chevron or splined device for the nozzles of the bypass and core ducts.

The effectiveness of this method makes up 0.5 EPN dB at take-off (average certification value for takeoff run and climb) [Solonin V.I., Khaletsky Yu.D. 2010]. An effective way to reduce the noise of a jet stream is to increase the bypass ratio. According to rough estimates, using a 3dB/m dependence, a power plant with a bypass ratio of m≈12 will reduce the noise level of the aircraft at control points by 9 EPN dB.

As is seen from the represented material, the aviation technologies and operational factors shall be designed in parallel so that to comply with the requirements of Silent Aircraft Initiative, which sets objectives of noise abatement outside of the perimeter of a typical urban region airport. The technologies were included in the conceptual design “Silent Aircraft”, ensuring slow and steep descending trajectory with offset landing threshold [Hall, C.A., Schwartz, E. and Hileman, J.I.,2009].

Due to using an improved airframe design in conjunction with a deployable drooped leading-edge, elevator displacement and thrust vectoring (Figure 4.56), for the “Silent Aircraft” developed was a short-length landing flight path with flight-path angle 39°. Upon that the engines are running idle so that to decrease the noise level and to diminish the heat resistance, which is required for aircraft holding.

Such an approach flight path ensures a peak noise level of 61 dBA outside of the airport perimeter, which is adequate to the background noise level. This procedure would comply with the manoeuvering requirements,

but it can affect the runway acceptance rate in the airport if such operations are not separated from the conventional landing approach procedures.

Adaptation of any aviation technology - researches, manufacture of prototypes, tests, integration - usually requires about 10 years. So that, if it is remembered that the change-over to a new type of fuel will take place in the middle of the century, then it makes sense already today to turn on other innovations: other aerodynamic airfoils and configurations, materials, and so on.

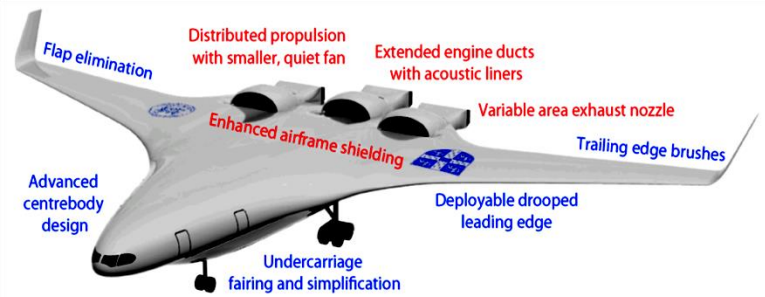


Figure 4.56: Design of Silent Aircraft SAX-40 involving key technologies of noise abatement

Until 2030, aircraft with a conventional-form fuselage and a conventional-form wing will prevail over the avant-garde constructions that are being developed to solve the problem of reducing aircraft noise. Aircraft of fundamentally new designs that provide further noise reduction in comparison with the concepts of 2010, at best can only appear by 2030. A good example of such an aircraft design is the concept with a double-bubble fuselage ("Double Bubble D8").

By 2030, engines based on fundamentally new concepts, such as bypass engines with ultra-high bypass ratio, contra-rotation open-rotor engines (CROR) and geared turbofan engines (GTF), can be created.

Bypass engines with an ultra-high bypass ratio are less noisy than modern engines [Khaletsky, Yu.D. 2014].Contra-rotation open-rotor engines (CROR) - Open Rotor (OR) with pushing propeller can be installed in the rear fuselage of a short- and medium-range aircraft (SMRA). However, the cumulative level of noise generated by them exceeds the level of bypass engines with ultra-high bypass ratio by not less than 15 EPN dB. Figure 4.57 shows the change in the bypass ratio in the process of the engine's evolution.

The group of experts (IEP2) held its analytical research of UHBR engines with a conventional scheme of frame-engine integration for the following aircraft categories: SMRA and twin-engine LRA (long-range aircraft). The research was held by comparing existing certification noise databases at each control point using an appropriate sample of the reference physical parameters. Based on the correlations obtained, the noise margins of the UHBR engines with a conventional scheme of frame-engine integration were obtained within the range of bypass ratios from 11 to 18 for SMRA and twin-engine LRA.

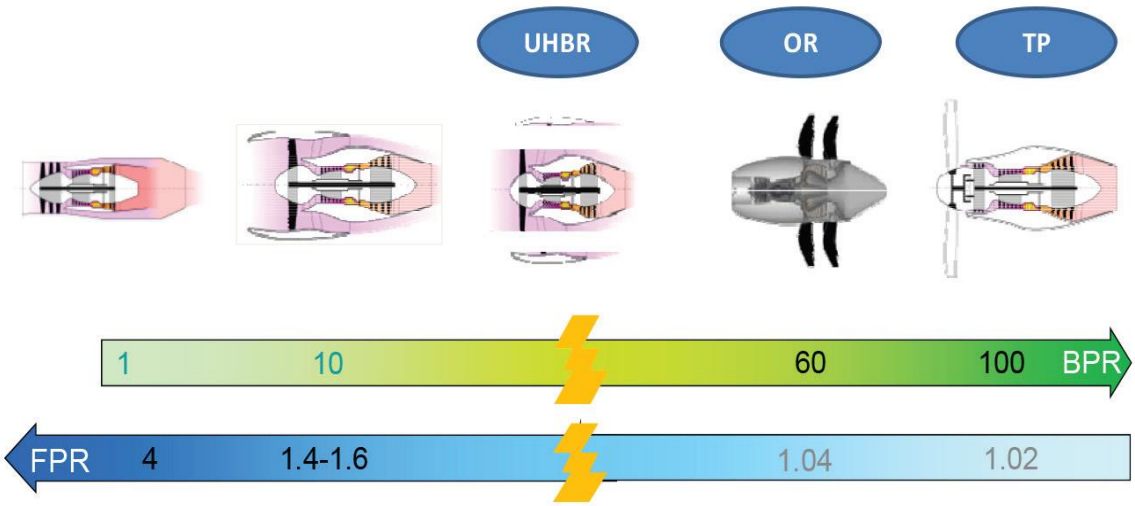


Figure 4.57: Bypass ratio in different engine schemes [Leylekian, L., Lebrun, M., Lempereur, P. 2014]

The potential of noise reduction for the aircraft with large turboprop engines, which consume less fuel compared to bypass engines, was also investigated, which is why it is expected to use them on large aircraft. The International Co-ordinating Council of Aerospace Industries Associations (ICCAIA) presented the results of research devoted to the analysis of aircraft noise levels with turboprop engines. The baseline aircraft chosen for this study was Bombardier Q400 (EIS 2001, take-off weight up to 30 tons, 6PW150A engine, 6 blades propeller made by Dowty). The noise reduction technologies included an improved air intake and compressor design and an increased number of propellers blades up to 8, resulting in a reduction in circumferential speed at the periphery.

The aircraft with open-rotor type engines can demonstrate higher fuel efficiency than by-pass engines. Only the concept of the open rotor was considered in application to the aircraft of the SMRA category. To evaluate the aerodynamic and acoustic characteristics, the test data of the scaled model in the NASA wind tunnel was used.

The constant stiffening of ICAO standards has contributed to the development of programs aiming at technologies creation for reducing aircraft and engine noise [Leylekian, L., Lebrun, M., Lempereur, P. 2014].In the paper [Nae, C. 2014] the level of technological readiness of the most promising technologies are assessed, as well as general integration into a new generation of Green Regional Aircraft (GRA), as a highly optimized configuration that meets the requirements for FlighPath 2050. The design features of aircraft for achieving the ACARE goals, i.e. fuel efficiency increase, acoustic emission and CO_2 emissions reduction, are analyzed in the paper [Szodruch, J., Grimme, W., Blumrich, F., Schmid, R. 2011]. One of the methods of noise reduction is an electric aircraft with More Electric Aircraft (MEA) technology [Baharozu, E., Soykan, G., Ozerdem, M. B. 2017].

The concept of a low-noise aircraft is considered in the papers [Hileman J.I., et al., 2007; Chevagin, A.F. 2015; Maldar, A., et al., 2008]. The Silent Aircraft Initiative (Figure 4.58) has developed a conceptual design for extremely low noise (61 dB outside the perimeter of the airport during the landing approach) of commercial aircraft using various technical and operational innovations [Hileman J.I., et al., 2007; Chevagin, A.F. 2015; Maldar, A., et al., 2008].

Using the example of the SAX-40, it has been shown that, based on the low-noise design of the aircraft and the ability to approach for landing at a steeper angle, a significant reduction in noise during landing is possible at a lower engine thrust. Low-noise technologies developed for Silent Aircraft may be suitable for upgrading existing aircraft.

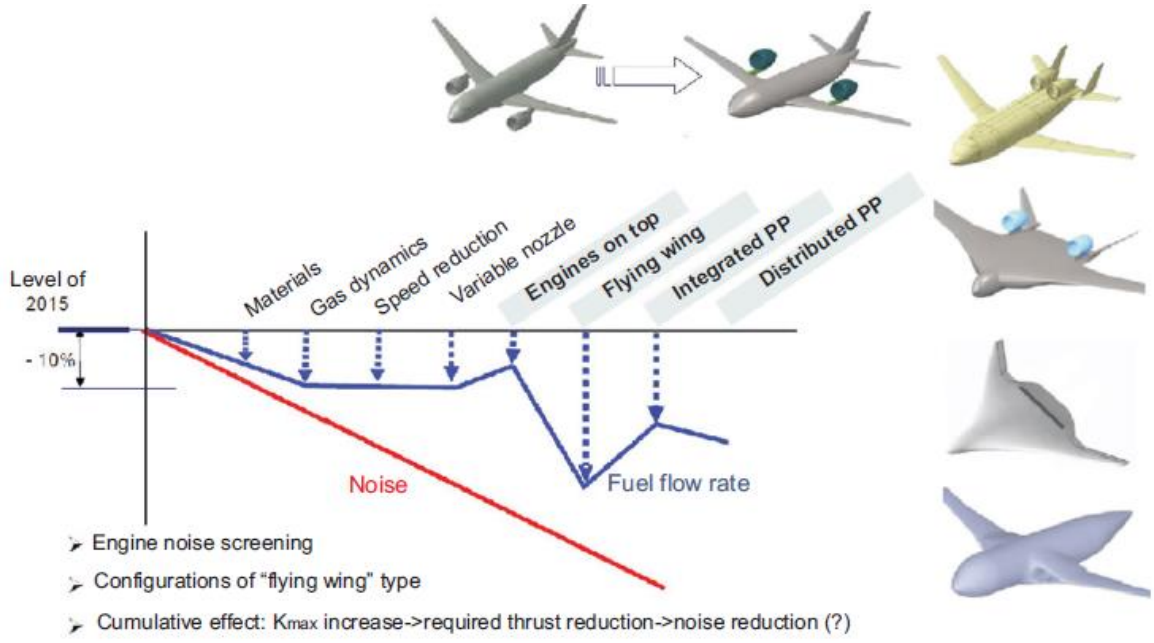


Figure 4.58: Non-standard aircraft layouts

Aircraft layouts other than the classic ones are possible, in which the engine's installation losses and the negative aerodynamic interference between the power plant and the airframe do not exceed the level adopted today, but give the background for reducing environmental noise (Figure 4.59) [Chevagin, A.F. 2015].

There are strict limitations on the safety and fuel efficiency conditions for placing the bypass engine on the airframe to implement the effects of engine noise screening. The placement of engines at the top of the wing behind the edge can be taken (for safety and fuel efficiency reasons) for consideration as a way of bypass engine noise screening in the front hemisphere. The jet stream noise screening in the rear hemisphere can be considered only in the dorsal layouts, for which interference losses can be minimized. Bypass engines in overwing layouts tend to dramatically deteriorate the aerodynamic characteristics of the aircraft. A diversion from the classical layout of the aircraft (Figure 4. 59) is likely to require an increase in the stall margins of the bypass engine in terms of inlet flow nonuniformity at limit conditions of the attack angles and slip of the aircraft.

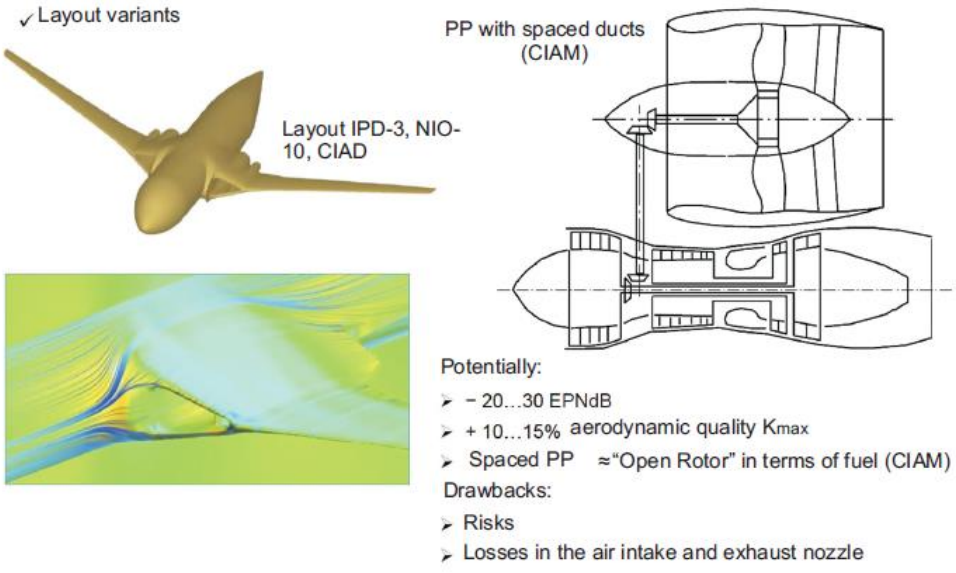


Figure 4.59: Built-in PP layouts with spaced ducts

For the next stage of exploratory studies of non-standard low-noise civil aircraft based on adequate Noise-Efficiency-Safety ratio evaluations, it is necessary to develop the methods of calculating the engine aeroacoustics within the aircraft. In the paper [Mincu, D.C., Manoha, E. 2014] different methods of acoustic emission calculation are compared when integrating the power plant with the aircraft, 3D models, computational meshes are presented (Figure 4.60). The computational model of the multiply-connected system "engine-attachment-frame" is presented in the paper [Baklanov, V.S. 2010].

The model is developed based on experimental researches of frequency characteristics of dynamic flexibilities and vibroacoustic conductance of the engine casing and the airframe structure in the places of supporting connections. This model allows us to develop several algorithms for the evaluation of acoustic processes in the engine gas flow duct, vibration characteristics of the power plant units (for example, plunger pumps) and dynamic loading of the engine mounts.

To achieve the ACARE goals, methods for calculating and predicting the noise level should be developed. The complete calculation structure should include modules for predicting geometric configurations, aerodynamics, flight mechanics, general aircraft characteristics and acoustics. Output results are fully predicted based on realized simulation models. The aircraft noise prediction program includes a function of flight path synchronization with Flight-Data-Recorder positions and aerodrome maps, aerodrome simulation, noise prediction throughout the flight, noise footprints, stochastic aircraft noise analysis in the presence of undetermined parameters.

The problems associated with calculating the reliability of some noise models and using these models for uncreated aeroplane configurations are discussed. In the paper [Havrilesko, B.R., et al., 2014] the capabilities of the software module for predicting the noise generated by modern aircraft during the climb, cruise flight and approach are examined. The calculation module was created in the MATLAB program. The authors of the paper emphasize that the calculations in this module are well suited for aircraft that are in operation, but for the calculation of future aircraft, it is not suitable and requires further development.

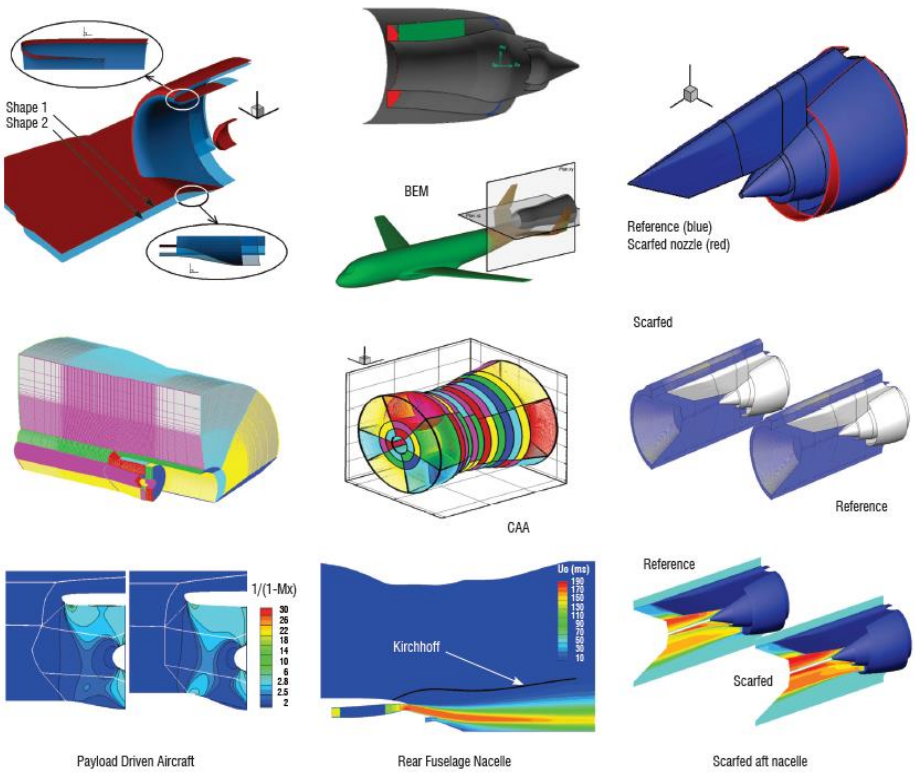


Figure 4.60: Elements of numerical simulation

In the paper [Redonnet, S. 2014] a hybrid noise prediction method developed in the Onera Research Center, France is considered. When developing and beta-testing the calculation methods, a very important issue is the availability of an acoustic characteristics database for the aircraft and individual elements.

A separate place is occupied by the methods for calculating fan noise. In the paper [Ferrante, P. et al., 2014], an innovative integrated approach to noise calculation has been proposed to predict noise from a fan in the front hemisphere with taking into account the design of the nacelle. The method is based on the use of an effective CFD solver that implements the Nonlinear Harmonic method for simultaneous calculation of noise sources and its expansion in the near field, considering aeroacoustic characteristics in the far-field. The results of the simulation were compared with the experimental data. The method of predicting the acoustic characteristics, proposed by the authors, has higher efficiency, takes less time and has higher possibilities for calculating acoustic characteristics; it can be used to predict the acoustic characteristics of impeller machines.

In the CIAM (Russia), a 3DAS solver calculation method was developed [Rossikhin, A., Pankov, S., Brailko, I., Mileshin, V. 2014]. Verification is carried out for the acoustic emission polar pattern of a high-bypass ratio fan (m = 8) for the first three harmonics. Authors conclude that the model has satisfactory results and needs to be improved.

In the paper [Timushev S.F., Gavriliuk V.N., Aksenov A.A., Klimenko D.V. 2017] a new highly effective method is proposed for numerical simulation of three-dimensional tonal acoustic fields at the blade passing frequencies and their higher and combination harmonics generated by an aircraft engine fan. The method is based on a direct solution of the Fourier - transformed wave equation in complex variables considering convection in a rectangular coordinate system with boundary conditions in the form of complex impedance. The noise source can be received by the acoustic-vortex decomposition method. The paper gives examples of verification and application of the proposed method of sound field simulation considering the boundary conditions in the form of complex acoustic impedance. Good perspectives of its application for the optimization of impeller machines are shown, including the tonal noise reduction of the bypass engine fans. The LMS software package is well proven in the calculation of acoustic characteristics.

The paper [Piatunin K.R., Arkharova N.V., Remizov A.E. 2014] presents the results of numerical simulation of the fan tonal noise using the LMS Sysnoise software package in the format of Exterior Direct BEM. The calculations are performed at the approach condition. The calculation results include acoustic emission polar patterns at a distance of 50 m from the engine in the front hemisphere. The simulation was made in a complete setting for all the blade channels of the wheel and the stator blades of the fan stage in the absence of axial symmetry of the stage. The article gives an assessment of the possibility of using the presented approach for analyzing the acoustic characteristics of aircraft engine elements. Also, the manpower input and computational burden required for simulation are presented.

The tone noise of the interaction between the fan and the add stages of the low-pressure compressor makes a significant contribution to the overall noise level of the aircraft engine, especially at subsonic conditions [KhaletskyYu.D., Korzhnev V.N., Pochkin Ya.S. 2016]. This noise is caused by the interaction of the fan and booster elements. The tonal components at these frequencies are the result of the nonlinear interaction between rotor and stator rows. Therefore, in the noise spectrum of the fan, in addition to the usual noise of interaction, the total and difference tones appear.

When studying the acoustic characteristics of a by-pass wide-chord fan, it was found out that the total and different components of the noise of interaction between the fan and the compressor appear at subsonic conditions and spread mainly over the front hemisphere.

In order to reduce the noise, researches are being held on the combined silencers of the fan noise, as well as the location of their installation. The results of the research [Khaletsky Yu.D., Shypov R.A. 2010] show that

the latticed silencer is broadband and universal. In one way or another, it reduces all noise components practically in the entire frequency range above 1.0 kHz approximately. On average, for four to five discrete components of noise, the sound power reduces for about 4 dB, that is, more than twice.

Also, researches on centrifugal and radial compressors and fans under carried out. For example, the paper [Wang, P., Zangeneh, M. 2014] presents the results of research on the aerodynamic and acoustic characteristics of a transonic centrifugal compressor. As a result of the blades reprofiling, the characteristics of a centrifugal compressor have improved. Aerodynamic performance has improved over the entire operating envelope, and acoustic characteristics have improved at the operating condition close to the maximum one.

In the paper [Mamaiev, V.K., Vlasov, E.N. 2009], an analysis of the dependencies of the sound power level estimation that were proposed by various authors was presented in the context of radial fans with a double inlet and a single-stage radial compressor with a bladed diffuser. A new formula is proposed for estimating the sound power level, taking into account both aerodynamic characteristics and geometric parameters. The authors proposed a correction factor that takes into account the geometric parameters of the impeller machines.

Particular attention is paid to the methods of gas-dynamic influence on the flow in fans and compressors for the reduction of acoustic emission in the source [Kohlhaas, M., Carolus, T.H. 2014; Doroshenko, E., Tereshchenko, Y., Lastivka, I., Tereshchenko, Y. 2017; Polacsek, C., et al., 2014]. The paper [Kohlhaas, M., Carolus, T.H. 2014] presents the results of the axial fan rotor-stator interaction, which is the source of tonal noise. The presented results show that the optimized sectional air blowing through the trailing edge makes it possible to reduce the sound pressure level by 2.4 dB, and on the first harmonic up to 21.4 dB, which practically indicates its elimination. The paper [Polacsek, C., et al., 2014] considers a method of reducing the broadband noise of a fan by an active influence on the flow. The studies have shown that an active impact on the boundary layer leads to a decrease in the aerodynamic wake behind the blade and helps to reduce broadband noise, but discrete noise can increase in this case. The results of the study presented in [Doroshenko, E., Tereshchenko, Y., Lastivka, I., Tereshchenko, Y. 2017]showed that the use of a double-row fan makes it possible to reduce the overall sound power level by 6.8 ... 7.4 dB.

The paper [Rybinskaya, L.A., Bul'bovich, R.V., Kychkin, V.I. 2017] provides an overview of methods for reducing jet noise. In various research programs, advanced methods for reducing the noise of a jet stream are investigated. These methods include liquid injection, the use of a bevelled nozzle, the use of micro-jets, high-frequency excitation. All of these methods have a potential noise reduction of 1-2 EPN dB for takeoff run and climb [Rybinskaya, L.A., Bul'bovich, R.V., Kychkin, V.I. 2017; Solonin V.I., Khaletsky Yu.D. 2010]. In order to reduce the jet stream noise, an analysis of known results of experimental studies for 5 researches was made using correlation method to identify the jet stream noise sources in the paper [Panda, J. 2005].

In the paper [Medviediev, V.V., Timko, O.S. 2012] a comparative analysis of methods for reducing the noise of an aircraft engine exhaust jet was made. It is shown that mixing the flows is practically the only way to improve the acoustic characteristics of the engine without deterioration of its economy. At high values of the bypass ratio (m>6...8), the positive effect of mixing on the economy is negligible and does not justify the increase in the mass of the engine due to the mixing chamber, but the acoustic effect remains. Therefore, for the engines with m<6, the use of a mixing chamber gives the best results, both in the economy and in acoustics. In addition, in such a scheme of the engine, acoustic processing of the nozzle walls and screening of the bypass duct with the mixer is possible, which allows reducing the fan noise emitted to the rear hemisphere, and screening of the core duct with the mixer and the decrease in the average rate of flow from the nozzle due to mixing reduces the noise of the turbine and the jet stream itself. These measures are implemented on the PS-90A2 engine.

In the paper [Bailly, C, et al., 2014], the structure of shock waves in a jet nozzle is studied. The mechanisms of interaction between the broadband noise and shock waves noise are considered.

The paper [Knobloch, K., et al., 2014] presents the experimental studies results of the acoustic characteristics of an A320 aircraft auxiliary power unit with different silencers. It is shown that the use of silencers allows reducing the level of sound pressure by 20 dB. Among all of the silencers studied, the authors highlighted a new PFW Aerospace AG silencer, which has high performance over a wide frequency range.

The introduction of the presented measures in the power plants with m <8 will allow reducing the total noise level of the jet stream at the control points, in the nearest decade it will be about 1.0-3.0 EPN dB. By increasing the bypass ratio the jet stream noise decreases due to the decrease of its velocity, which is estimated at 3-4 EPN dB at the points of takeoff run and climb [Solonin V.I., Khaletsky Yu.D. 2010]. Currently, the contribution of the core duct noise into the total noise of the aircraft at certified points is much lower than the noise of the fan, jet stream and airframe. Nevertheless, with an increase in the bypass ratio of the engines and the introduction of effective methods for reducing the noise of the fan, the jet stream and the airframe, an increase in the share of the core duct is expected. The sources of the core duct noise are the turbine, the combustor, the bleed valve and the compressor [Solonin V.I., Khaletsky Yu.D. 2010].

The decrease in the acoustic pressure level of the compressor and the turbine is aimed at optimizing the number of rotor wheel blades and stator vanes, optimizing the gaps in order to reduce the wake interaction, and optimizing the aerodynamic design of the blades. The paper [Nordwall, G., Demeulenaere, A., Ferrante, P. 2014] presents the results of numerical simulation and physical experiment to improve the acoustic characteristics of a radial turbine. The paper shows that the initial radial turbine had significant hydraulic losses associated with a separation flow. More than 50% of the blade passage was occupied with separated flow. After optimizing the geometric parameters of the turbine in order to improve the aerodynamic characteristics, the acoustic characteristics of the initial turbine and the optimized one were investigated. As the research results showed, the level of acoustic power of a radial turbine with optimized geometric parameters decreased by 9 dB.

In the paper [Serrano, A., Fernández, J.R. 2014] the modal characteristic of a low-pressure turbine is investigated. As a result of the research, a radial structure of modal noise during rotation is obtained, which makes it possible to study in more detail the mechanism of noise generation at a supersonic flow in a turbine. The data processing in the evaluation of acoustic power is described in details. Acoustic characteristics were measured with a special device that rotated with the NMM turbine. High-temperature noise silencers (composite sound-absorbing structures), lining of the nacelle mixing chamber are used for acoustic efficiency of the core duct. For the reduction of the combustion chamber noise, studies are being conducted aimed at research on the noise sources in the combustion chamber and the mechanism for generating acoustic emission.A promising method of reducing the turbine noise is the acoustic lining of its flow section above the wheel [Solonin V.I., Khaletsky Yu.D., 2010]. The effectiveness of the method has been verified for a fan [Khaletsky Yu.D., Shypov R.A., 2010].

The paper [Grimm, F., et al., 2016] presents the results of a turbulent combustion noise analysis for small Mach numbers in a combustion chamber model. A hybrid approach is used to predict acoustic characteristics. The calculation results showed that this computational method FRPM-CN is rational from the point of view of reliability, computing time and accuracy of results. The mechanism of generating the acoustic emission in the reverse-flow combustion chamber of a gas turbine engine was investigated in [Duran, I., et al., 2014].

Reducing the noise of the combustion chamber may be obtained with the use of a sleeve turbine fairing as a silencer, formed as a Helmholtz resonator with a neck in the form of a microperforated membrane and folded cavities separated by a grid baffle. The efficiency of these silencers is estimated at 4-9 dB in a narrow frequency range and 3-4 dB for the total noise level. In addition, the use of curved and inclined turbine blades

will reduce turbine noise and at the same time prevent the noise of the combustion chamber from expanding downwards due to a higher acoustic impedance at the combustion chamber outlet.

Among the methods to reduce the noise of the combustion chamber are: a multi-stage combustion chamber, injectors with aeration instead of high-pressure injectors, an increase in the cross-section of the flow channel in the combustion zone. However, in studying the methods for reducing the noise of the combustion chamber, emission characteristics must be taken into account.

Reduction of the bleed valve noise can be provided with an output perforated screen (decrease in the noise of an isolated unit reaches 10 EPN dB, with the total aircraft noise level decreasing by several EPN dB units). An advanced method to reduce the bleed valve noise is the jet dispersion by means of a toothed orifice, its efficiency is estimated at 5-7 dB relatively to tonal noise [Solonin V.I., Khaletsky Yu.D., 2010].

In turboprop engines, the issue of noise reduction is associated, first of all, with a reduction of the propeller noise. Reducing the noise of propellers is based on changing the number of blades, optimizing their shape, using an active noise reduction system. An important place is taken by the issues of prognosticating the propeller acoustic emission and the mechanism of noise generation.

In the paper [Tan, Ch.H., Voo, K.S., Siauw, W.L. 2014] the known data of a physical experiment are compared with the results of numerical simulation of the eight-blade propeller acoustic characteristics at Mach number equal to 0.6. The results of the calculations show a good correlation between the results of physical and numerical experiments.

As a result of the computational-experimental study of the blade number and diameter influence on the propeller noise, it was established that the aeroacoustic optimization of the propeller by means of increasing the number of blades and changing the diameter is achieved, primarily, due to the reduction of noise from aerodynamic loading when the number of blades increases [Moshkov, P.A., Samokhin, V.F., 2016]. It has been experimentally established that an increase in the number of blades leads to a decrease in the acoustic efficiency of propeller-driven power plants.

In the paper [Zimcik, D.G. 2004], a method of active noise reduction in the cockpit of a propeller aircraft is considered. It is shown that even without propeller synchronization, it is possible to achieve a 3-6 dB reduction in the acoustic pressure level.

The trend analysis of the aircraft engines noise reduction has shown that the technological advance will allow reducing the fan tonal noise by 2-4 dB, and the broadband noise by 1-3 dB. In this case, the influence of the stator blades sweep and inclination on the tonal noise emitted into the rear hemisphere is expected to be in the range of 3-5 dB.

Thus, in solving the problem of the fan noise reduction, an important role is played by: reducing the fan rotor speed, applying the composite materials in the fan blades design, aerodynamic and acoustic optimization of the fan blade profile, considering the effects of interaction between the fan rotor and stator blade rings, using an acoustically optimized stator blades. Application of these methods will reduce the tonal noise of a fan by 2-4 dB, and the broadband noise by 1-3 dB. In this case, the use of acoustically optimized stator blades will reduce the tonal noise emitted in the rear hemisphere by 3-5 dB.

It is expected that the implementation of the results of the planned studies on aeroacoustic characteristics of the variable-area nozzle of the fan, the stator blades rings SAS, the noise silencers installed above the rotor wheel, the rotor wheels and stator blades of the fan with active interaction elements, the hubless fan will additionally reduce the noise by 1-3 dB.

When reducing the engine noise, acoustic optimization of the nacelle takes an important place. Application of seamless SAS, bevelled air intake will reduce the suction noise by 1-4 dB. The use of active-passive SAS

can reduce the tonal noise by 2-7 dB.The use of a chevron or splined device in the nozzles of the bypass or core duct of aircraft powered by bypass engines with a bypass ratio of m = 4 ... 6 will reduce the jet stream noise by 1-3 EPN dB. The reduction of the jet stream noise during take-off for the engines with a bypass ratio of m = 7 ... 9 due to the use of a chevron or splined device for the nozzles of the bypass and core ducts makes up 0.5 EPN dB. With an increase in the bypass ratio, the effect of the chevron nozzles is decreased, and therefore the investigation of various methods for reducing the jet stream noise plays an important role. The use of micro-jets, whose influence is based on the aerodynamic interaction between the peripheral jets and the main one, can reduce the low-frequency noise by 1-2 dB, while the thrust value remains the same. Plasmatic actuators can reduce the jet by an average of 1.3 dB, their designs are simple, as they are integrated into the surface and do not have moving parts. A multi-tube nozzle provides a decrease in the total acoustic power of the flow by an average of 8 dB, while the part of low-frequency components decreases and the noise spectrum shifts to a higher frequency sector when compared with a round nozzle due to an increase in the surface of the jets mixing with the environment in the area near to the nozzle exit area.

The use of mesh screens reduces the total acoustic power of the flow by an average of 5 dB, leads to a decrease in the share of low-frequency components and an increase in the share of high-frequency noise components. The effectiveness of mesh screens increases in combination with other methods of noise reduction, for example, SAS (Figure 4.61). Screening the jet stream noise with a secondary gas flow can lead to a noise reduction of up to 5-7 dB in the high-frequency area of the acoustic spectrum. An ejector noise-suppression nozzle with a multi-element outlet leads to the disappearance of discrete components in the jet stream spectrum (Figure 4.62), while the noise of the jet stream decreases by an average of 10 dB. However, a significant disadvantage is weight gain, reaching 6%.The use of acoustic influence is difficult in practice due to the complexity of the application, but this method allows reducing the noise level of the jet stream by 2-3 dB. Screening of jet stream noise, based on the phenomenon of acoustic waves diffraction, allows reducing the noise level up to 3.5 dB.

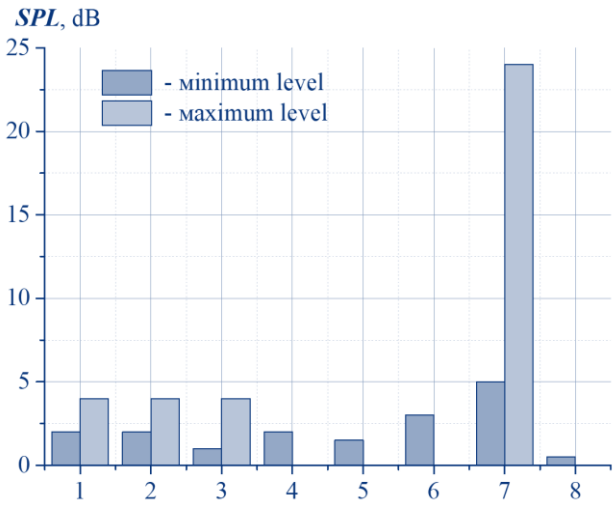


Figure 4.61: Effectiveness of methods for reducing the noise level in the fan: In Figure the numbers indicate the positions: 1 - sweep of the rotor wheel blades; 2 - sweep and inclination of the fan stator blades; 3 - optimization of the rotor wheel circumferential speed; 4 – variable-area fan nozzle; 5 – stator blades with SAS; 6 – rotor wheel with noise silencer; 7 – rotor wheel and stator blades with active influence; 8 - hubless fan

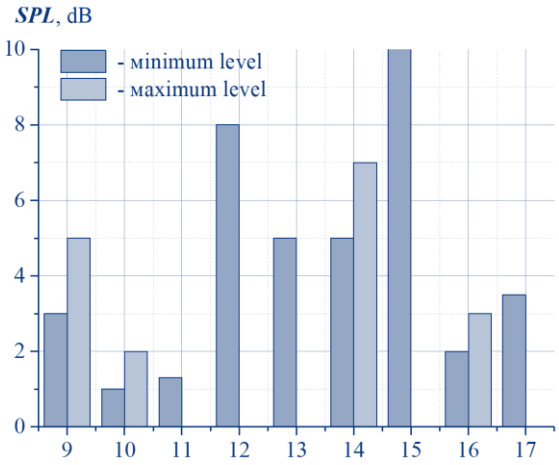


Figure 4.62: Effectiveness of methods for reducing the level of jet stream noise: In Figure the numbers indicate the positions: 9 - chevron nozzle; 10 - microjets; 11 - plasmatic actuators; 12 - multitubular nozzle; 13 - mesh screen; 14 - screening of jet stream noise by secondary gas flow; 15 - ejector noise-suppression nozzle with a multi-element outlet; 16 - acoustic impact; 17 - noise screening

In order to meet ICAO future requirements, to achieve ACARE noise reduction goals, it is necessary to develop breakthrough technologies, which include the development of engines of new structural layouts, the use of active, adaptive, hybrid methods to reduce the noise of aircraft engines. At the same time, the introduction of breakthrough technologies shall be made without the loss of efficiency of the power plant.

Key technology projects for Engine Noise reduction(Figure 4.63) in Japanese Noise Technology Research Programs are the *aFJR* (advanced Fan Jet Research) *project* and *Green programs* (both completed in FY2017) [ICAO CAEP/11-IP/11, 2019]:

- JAXA's aFJR project proposed a lightweight acoustic liner panel made from resin; Fan rig test in an acoustic facility confirmed noise reduction similar to the conventional AI-based liner panel.
- **Green engine program** involved noise reduction technologies including a "notched nozzle".JAXA an d IHI have demonstrated acoustic and aerodynamic performances of the notched nozzle. Microjet was also studied through an international co-operation.

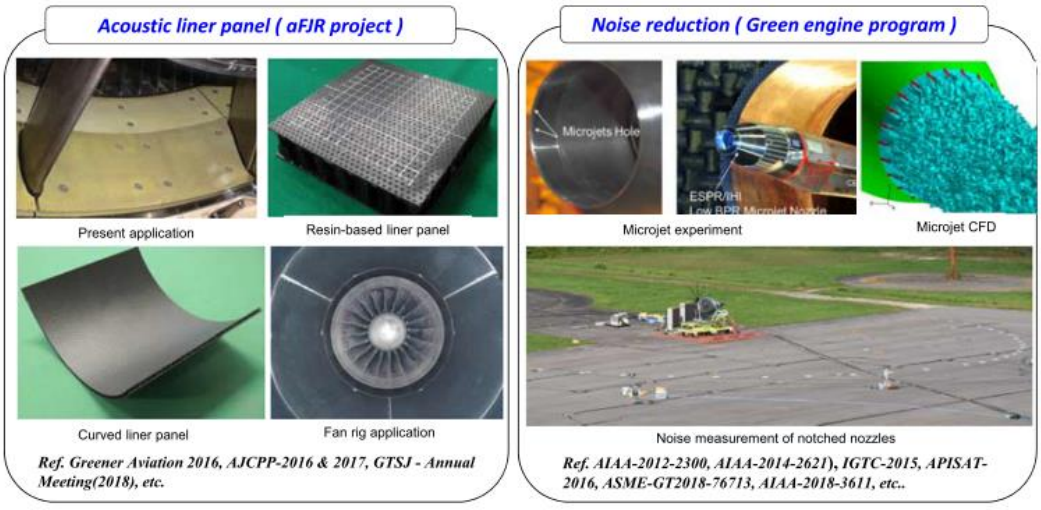


Figure 4.63: Key Japanese technology projects for Engine Noise reduction

Russian Technology Research Programs "Development of aviation industry 2013 – 2025" (including subsonic and supersonic aircraft, helicopters, novel aircraft concepts, engines,) and «Research and development on priority directions of development of a scientific and technological complex of Russia for 2014-2020» (advanced methods, liners, installation effect, beamforming), including participation in Horizon 2020, provide the development of Green Engine and Acoustic Liners for PD-14, its installation effect and airframe noise for MS-21, and novel aircraft concepts for SuperJet SV, Figure 4.64 [ICAO CAEP/11-IP/11, 2019].

The following constitutes UK Sustainable Aviation's judgement concerning each of the above three bullet points, and should not be interpreted as a statement of intended product strategy. The decision to launch a new aircraft product is influenced not only by technology readiness but by many other factors such as the market demand, maturity of the in-service fleet, the prevailing economic situation, regulatory pressures and oil price predictions, etc. UK Sustainable Aviation assumed EIS dates for *Generation 2 aircraft* are as follows [Sustainable Aviation Noise Road-Map, 2018]:

Regional Jets

- An EIS of 2050 is chosen for the small aircraft subdivision
- An EIS of 2035 is chosen for the large aircraft subdivision

Single-Aisle

- An EIS of 2025 is chosen to reflect a balance between several competing factors. Although 2025 will be only some 10 years after the introduction of the Generation 1 aircraft in this category, the Generation 1 aircraft are re-engined versions of existing aircraft and it is expected that technological developments will result in the introduction by 2025 of an all-new aircraft type.

Twin-Aisle

- We assume a gap of approximately 20-25 years between Generation 1 aircraft and their successors in this category, leading to an approximate EIS of 2035 for the small aircraft subdivision
- We assume an EIS of 2040 for the medium aircraft subdivision.
- We also assume an EIS of 2040 for the large aircraft subdivision.

Very-Large

- We assume a gap of approximately 30 years between Generation 1 aircraft and their successors, leading to an approximate EIS of 2040.

These dates correspond to the EIS dates of the SA CO_2 Road-Map [Sustainable Aviation Decarbonisation Road-Map, 2020] except that additional categories and dates have been introduced since a finer level of granularity is required for noise.

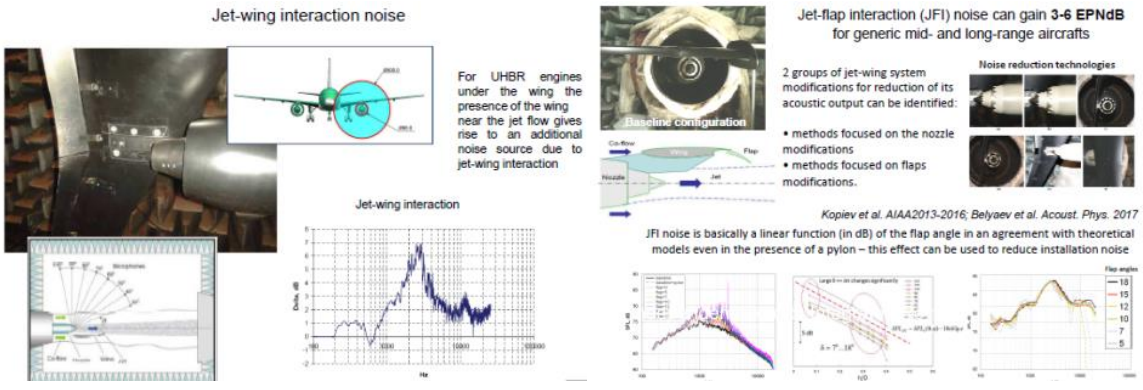


Figure 4.64: Installed jet noise investigations in RF aircraft noise programs

4.1.2. Aerodynamic Noise

The progress in the reduction of engine noise implies that: (i) it remains the dominant noise source at take-off and with cut-back in climb; (ii) on approach to land, with the engine at idle, the aerodynamic noise can

predominate. Thus overall noise reduction at airports requires consideration of not one but two classes of noise sources;

- *Engine noise sources* such as fan, turbine and jet noise, combustion and buzz-saw (shock waves) noise with tonal and broadband components;

- *Aerodynamic* (or *airframe*) *noise* from the extended undercarriage and its wells and other cavities, and the deflections of control and high-lift surfaces (flap and wing trailing edges, flap and slat side edges, spoilers, component interaction noise), sources associated with the fuselage and wing turbulent boundary layers at aircraft flyover noise measurements. Among these noise sources, landing gears and high-lift devices including slat and flap were identified as the two major airframe noise contributors.

Depending on the noise mechanism various measures can be taken to reduce the noise at the source or to reduce the effects of its emission. Noise reduction measures may not be additive, with the overall noise reduction less than the sum of the parts. The overall noise exposure of near airport residents can be reduced by land planning and by operational measures. The effects of noise on the near airport residence can be addressed at all of 7 links in a long chain: (i) the noise of an isolated engine in a test stand; (ii) the noise of the engine installed in aircraft subject to reflections; (iii) the noise in flight with flow effects and aerodynamic noise sources; (iv) the modification of sound by wind, turbulence, stratification and dissipation while propagating in the atmosphere; (v) the effect of different types of ground (concrete, snow, soil) and obstacles (terrain and buildings) in sound absorption and interference; (vi) the outdoor to indoor sound transmission through windows and other apertures; (vii) the psychoacoustic effects depending on the different types of activity: sleep, study, talking or other tasks. All the factors can play a role in the "noise annoyance", which can motivate noise restrictions at airports.

Due to the complexity of airframe components and vastly different noise mechanisms, and the increasing strict noise reduction target set by the ICAO, airframe noise reduction has been facing a lot of challenges. Starting from a low noise design, the only technology which may be available for additional noise reduction uses flow control, today at TRL 1 to 2 (Figure 4.65). The expected noise reduction is no more than 1 dB at the component level, which is additive to the benefit of the low noise design but is so small that it would be not very significant at the aircraft level.



Figure 4.65: Airframe noise reduction technologies

The IEP concluded [ICAO, Doc 10127, 2019] that no additional noise reduction can be expected for a conventional configuration (under the wing installed engine). It appears that the only way to obtain more landing gear noise reduction at the approach condition seems to be the development of fuselage-mounted

short landing gear, which of course necessitates a corresponding change of the aircraft structure, as described in [Dobrzynski W. M., 2005].*High lift devices*– slat and flap – with low noise designs (including, in particular, the slat cove filler), today at TRL 1 to 2 are expected to be at TRL 6 by 2020 with a potential of 5 dB maximum reduction at the component level. The current TRL of these technologies is too low and the benefits too uncertain to obtain credible estimates on the benefit at the aircraft level which in any case will be small with conventional aircraft configurations.

Based on the current understanding of the noise source mechanism in the slat cove/slot area, add-on devices have been developed to reduce the broadband noise. Such devices are slat cove cover, slat hook extensions and slat cove filler. It was applied a slat cove cover to attenuate the strength of the vorticity in the free shear layer between the cove and the slot flow, and the comparison of A-weighted 1/3-octave sound pressure level (SPL) in the far-field showed a promising broadband noise reduction using the cove cover (Figure4.66a). This concept was extended by attaching an extended blade seal to the slat hook and documented a further noise reduction potential compared to the cases of no blade seal and baseline blade seal (Figure4.66b). Furthermore, a slat cove filler designed to fill the slat cove through a streamlined body and their microphone array measurements presented a significant noise reduction potential of 4–5 dB in a broadband frequency range (Figure4.66c).

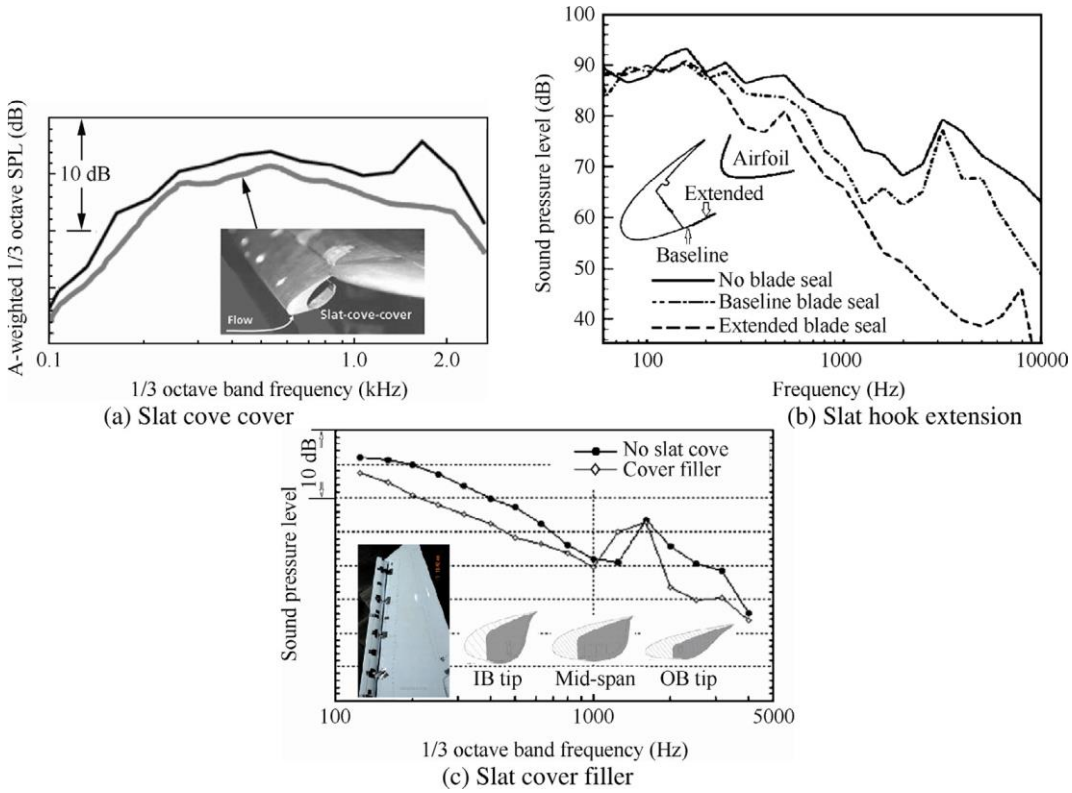
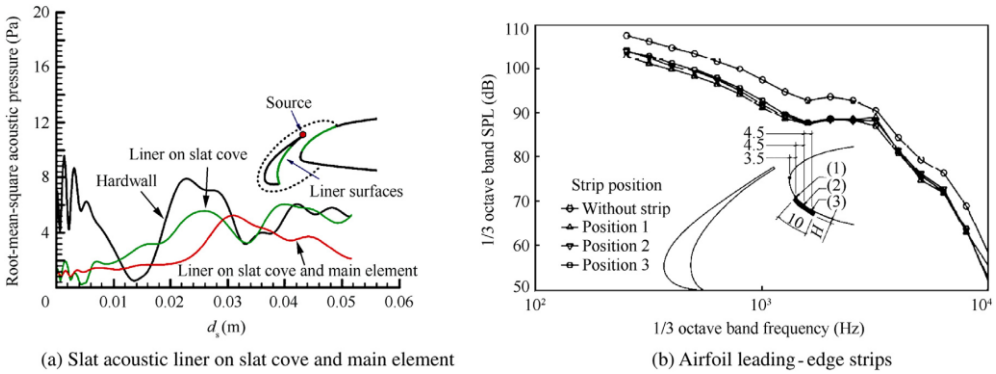


Figure 4.66: Noise reduction potential of a slat cove cover, slat hook extension and slat cover filler

For the slat trailing-edge noise control, transparent edge replacements, such as porous material or edge brushes, were used to alleviate the transformation of boundary layer flow turbulence into propagating sound waves. All of them were shown to be very effective in trailing-edge noise reduction. Other than the above-mentioned control methods that directly affect the noise source mechanisms in the slat cove and trailing edge, the acoustic liner is aimed at the attenuation of sound waves on their propagation path between the slat cove and the wing leading edge, i.e. to alleviate the fluid-structure interaction to reduce noise. Acoustic liners were utilised on the slat cove surface and the upper surface of the airfoil leading edge. Compared with the hard wall of the slat, the acoustic liner on slat cove surface and main element provided a meaningful acoustic pressure reduction along the slat gap (Figure 4.67a). In a similar way, strips with sufficient thickness

were applied on the pressure-side surface of the airfoil leading edge and showed that noises in the near and far-field were attenuated significantly (Figure 4.67b).

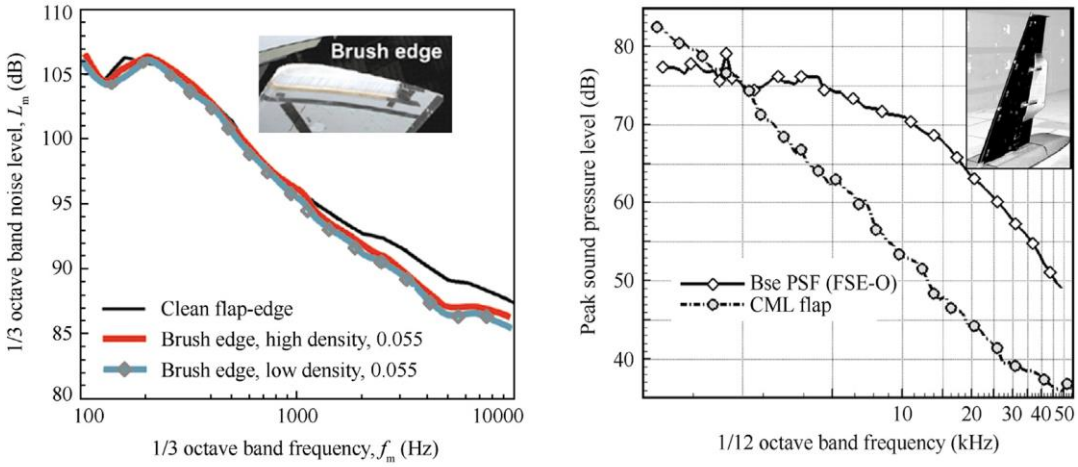


(a) Slat acoustic liner on slat cove and main element

(b) Airfoil leading-edge strips

Figure 4.67: Noise reduction potential of a slat acoustic liner on slat cove and main element and airfoil leading-edge strips

As for the flap noise reduction, edge flow modifications using side-edge treatments, such as added-on side-edge fences, porous flap edge and edge brushes) proved to be very effective (Figure 4.68). Aerodynamic tests showed that these treatments led to the formation of significantly weaker side-edge vortex system and the elimination of the bursting of the side-edge vortex. Both effects resulted in a decrease in the radiated noise.



(a) Using brush-type edge replacements

(b) Using continuous moldline link

Figure 4.68: Side-edge noise reduction using brush-type edge replacements and continuous moldline link

The landing gear broadband noise is normally generated by the turbulence flow separation of the bluff-body components and the subsequent interaction of such turbulent wake flows with downstream located gear elements. The turbulence-related noise and interaction noise are normally governed by the flow turbulence characteristics and the local impinging flow velocity. Since sound intensity increases with flow velocity to the power of 6, it can reveal that the beneficial effect of reduced local inflow velocity is more substantial than the adverse effect on the noise of increased turbulence intensity, as mentioned by [Dobrzynski W., 2010]. Based on the knowledge of landing gear noise source mechanism, an effective way to reduce landing gear noise is to cover most of the gear components behind a fairing. It was demonstrated that a total noise reduction of 10 dB could be achieved if the entire gear structure was covered by one fairing to appear as a streamlined body, Figure 4.69. Such fairing design, however, prevents the retractability of the landing gear and is thus impractical. Nevertheless, the work elucidates the potentially optimal noise control outcomes that can be possibly achieved [Dobrzynski W., 2010].

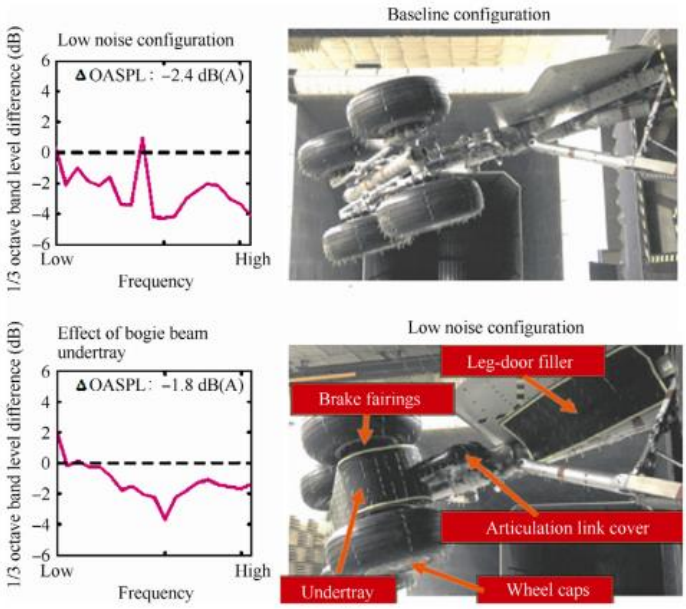


Figure 4.69: Example of the noise reduction potential of A340 full-scale main landing gear fairings [Dobrzynski W, Chow LC, Guion P, Shiells D., 2002]

Most of the novel airframe/engine concepts currently being developed and evaluated within the aviation industry today have to be viewed as one integrated system and cannot strictly be assessed separately. The low noise characteristics of these concepts are partly due to the shielding of the engine noise (fan inlet, fan exhaust, core and jet, Figure 4.53) by the Blended-Wing-Body (BWB) and partly airframe noise reduction features such as low-noise landing gear and the omission of flaps. Benefits of about 11 EPNdB cumulative were quoted relative to a conventional State-of-the-Art reference aircraft but more research is in progress on those noise reduction features as well as installation effects before these noise reduction concepts can be quoted with reasonable confidence.

4.1.3. Noise Abatement Operating Procedures

The noise of aircraft is subject to ICAO certification rules that are intended to apply worldwide. This does not prevent local authorities from applying stricter noise standards at specific airports. For example, the noise limits at a major airport like Heathrow cannot be ignored by the main airliner manufactures Airbus and Boeing. Local airport rules can include noise limits, curfews and fines on excessive noise levels. These measures can limit the capacity of airports by reducing the operating hours and they can affect the economics of flight by limiting take-off weight and payload. The certification rules do not cover interior noise, though airlines may have their standards.

Noise abatement operational procedures are being employed today to provide noise relief to communities around airports from both arriving and departing aircraft. PANS-OPS, Volume 1, contains guidance for the development of a maximum of two noise abatement departure procedures (NADP's) designed generally to mitigate noise either close in (NADP 1) to the airport, or further out (NADP 2) along the departure path. Review [ICAO Document 9888, 2010] contains a list of current NADP's in use by air carriers for a wide range of aircraft types. A number of them were assessed during EU Silence(R) project for their possible contribution to ACARE 2020 goal (Figure 4.70).

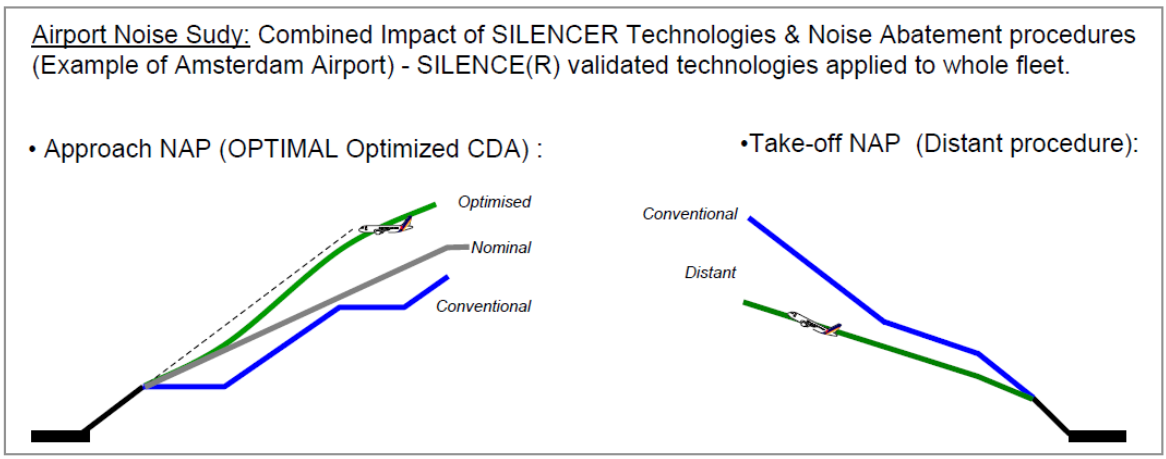


Figure 4.70: Departure and approach noise abatement procedures

Operational procedures can often be implemented with the existing fleet and have the potential to make an immediate improvement in the environmental impact of aviation. Noiseabatementoperationalproceduresinusetodaycanbebrokendownintothree broad categories:

Noise abatement flight procedures:

- Continuous Descent Arrival (CDA)
- Noise Abatement Departure Procedures (NADP)
- Modified approach angles, staggered, or displaced landing thresholds
- Low power/low drag approach profiles
- Minimum use of reverse thrust after landing

Spatial management:

- Noise preferred arrival and departure routes
- Flight track dispersion or concentration
- Noise preferred runways

Ground management:

- Hush houses and engine run-up management (location/aircraft orientation, time of day, maximum thrust level)
- APU management
- Taxi and queue management
- Towing
- Taxi power control (Taxi with less than all engines operating)

The NAPs listed above can make a measurable contribution to reducing noise levels and other environmental benefits in the vicinity of airports [ICAO Document 9888, 2010]:

— 3 to 12 dB noise reduction, and 8% to 36% reduction in noise contour areas on approach;

— 2 to 9 dB noise reduction and 23% to 42% reduction in noise contour areas on departure;

— As much as 35% reductions in CO_2, HC and NO_x and 50 to 1000 pounds of fuel savings per landing; and

— 90 to 630 kg CO_2 and 60 to 440 pounds of fuel savings per departure.

The magnitude and scope of the reductions, as well as the specific procedures to be used to achieve them, should be determined through a comprehensive noise study. The study should also include an analysis of emissions impacts and fuel burn, as these variables may be affected by procedure changes both in the air and on the ground. The aircraft operators and ANSP should be parties to the study to ensure the safety and

feasibility of the procedures and to take advantage of their technical expertise. The environmental benefits of some operational procedures are straightforward and easy to visualize preferential runways or flight tracks move aircraft away from more noise-sensitive locations. Conversely, the benefits assessments for NADP's and CDA procedures are extremely complex and may require detailed modelling to be well understood. It is imperative that accurate aircraft operating data and specific operator flight procedures are applied as input to the noise and emissions models and that impacts on airport and airspace capacity be analysed. It is worth repeating that some noise abatement operational procedures may increase emissions or derogate airport capacity while providing significant noise relief. Appropriate consideration of all potential environmental impacts is essential, particularly as priorities change and procedures evolve or come up for review.

CAEP Independent Expert Panel (IEP) [ICAO, Doc 10127, 2019] evaluated NAP methods, how and when they might be used to supplement new noise reduction technology developments in the next 10 years, to further reduce noise exposure around the airport community, as well as during climb and descent. A very significant improvement in cumulative noise reduction is expected from the introduction of NRT and increased BPR, but this improvement is not expected to be the same between take-off and landing, most of this improvement occurring at take-off (lateral and flyover) with much smaller benefits predicted at approach. In general, the benefits at landing/approach are ~3 to 4 dB less than at the departure. The main contributor at landing, at least for the SMR and LR classes of aircraft, is the undercarriage-generated noise, even when engine noise has a no negligible contribution. So the difference between take-off and landing suggests a difference in the potential role of operational procedures for aircraft noise reduction. NAP may useful for reducing noise exposure at take-off, but may be essential for the final approach, depending on what noise levels are ultimately deemed acceptable.

Continuous descent approach (CDA) is still under study, mainly to save fuel, but noise exposure reduction is also a benefit of this procedure. The challenge is to combine the aircraft deceleration and the rate of descent from the end of the cruise to the final approach (with the gear down), under ATC rules. To avoid increasing noise exposure, the trajectory adjustments have to be minimized in particular at low altitude, and the gear operation cannot be earlier than in the current practice. As the engines, during this phase of flight, are at or close to idle, the noise reduction technologies and increased BPR have no appreciable noise exposure benefit.

In order to exploit new technology and low noise operations developments, and to enable integrated impact mitigation solutions, it was considered of utmost importance to [Collin D., 2016]:

- Improve and continuously update the understanding of how noise from air transport operations affects people, with a significant focus on the influence of non-acoustic factors. Figure 4.71 provides a rough survey of the most important non-acoustic variables for long-term annoyance and annoyance at night.
- Provide technical support for the successful implementation of planning policies compatible with traffic growth for the long-term benefit of the communities. This will require specific thematic research aimed at better integration of land use planning (LUP) in decision making.

Consistent with this comprehensive strategy, a number of "Enabling Factors" are foreseen as key contributors to the 2050 noise goal achievement, namely [Collin D., 2016]:

- Improved numerical simulation capabilities, together with test facilities incorporating advanced measurement techniques, in order to support further noise reduction at the source level, and the implementation of multi-disciplinary optimization techniques and aircraft/engine integrated design practices that contribute to lower noise through efficient integration of noise reduction solutions, reduced weight, decreased drag, improved power plant efficiency, and enhanced flight path design.
- Stimulated advances in related technology areas, such as materials and electronics, to allow the introduction of novel low noise technologies, including active/adaptive techniques.
- Updated, and internationally recognized, annoyance and sleep disturbance models, that take into account the evolution of aircraft noise signatures and traffic conditions (multiple events), and that consider airport specificities.

- Improved tools to support transparent communication policies that cover relevant indices, online forecast and tracking flight path operations, and comprehensive assessment of environmental interdependencies, and the monetization of impacts.

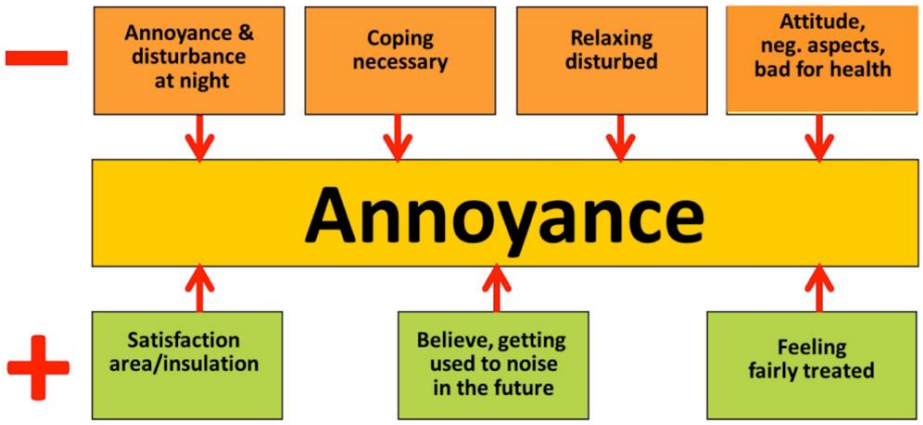


Figure 4.71: Overview of most important non-acoustic factors contributing to aircraft noise annoyance [Collin D., 2016]

EU project ANIMA [Dimitriu D., Heyes G., Hooper P., 2018] stands for "Aviation Noise Impact Management through Novel Approaches" is people-oriented research with aims at identifying and diffusing best practices to lower the noise annoyance endured by communities around airports. The project also tries to better understand the non-acoustical factors, which influence noise annoyance, but also to improve the quality of life of communities surrounding airports.

In the past years, huge efforts have been put on the reduction of noise at source. These efforts were conveyed through numerous projects, many of them having been supported by the successive R&D Framework Programmes of the European Commission. Clean Sky and SESAR are probably the best-known of these projects and they are the last stage of a continuous chain of studies which started in the last years of the twentieth century. Clean Sky integrates numerous bricks of "Noise Reduction Technologies" in platforms of demonstration and SESAR implements "Noise Abatement Procedures" for the Single European Sky. The aircraft noise per operation – to say per landing or take-off – actually and significantly decreased, - but not the annoyance! Several studies have shown that the annoyance due to certain levels of aircraft noise has increased around major airport hubs. In reality, this demonstrates the importance of the notion of annoyance. Annoyance to aircraft noise might be thought of as just a perception or feeling out it is a fact to be taken into account.

The key point of ANIMA (not a technology-driven project): understanding where is the annoyance within the noise; understanding to what extent noise is the actual source of complaints about noise-assigned annoyance; understanding if and how other environmental features may compensate the noise burden and help to tolerate possible traffic growth. The results of ANIMA project (finishing in 2021) will contribute in understanding of noise annoyance and in managing it with novel approaches [Dimitriu D., Heyes G., Hooper P., 2018].

The ACARE SRIA confirmed the importance of addressing the impacts aspects as part of a coordinated research strategy, stating that the targeted 65% noise reduction relative to the 2000 baseline "should be achieved through a significant and balanced research programme aimed at developing novel technologies and enhanced low noise operational procedures, complemented by a coordinated effort providing industry, airports and authorities with better knowledge and impact assessment tools to ensure that the benefits are effectively perceived by the communities exposed to noise from air transport activities".

4.1.4. Local Emissions of the aircraft

There are growing concerns about the impact of aviation on the atmosphere concerning local air quality (LAQ) and the associated human health and welfare impacts. Aviation emissions in airports are produced by aircraft, support vehicles and ground transportation dominantly. The emissions from these sources fall into two categories: emissions that cause deterioration in local air quality and emissions that cause climate change. Emissions that cause climate change from aviation also fall into two categories. The first category is GHGs, which are gases that cause climate change by trapping heat in the atmosphere. These emissions are produced when fossil fuels are combusted. Secondly, emissions from aircraft can alter radioactively active substances, trigger the formation of aerosols and lead to changes in clouds. Together these effects are known as radiative forcing.

LAQ issues are caused by Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x) and Particulate Matter (PM_{10} and $PM_{2.5}$). In high concentrations, these pollutants have been shown to cause health effects, among them to exacerbate a range of cardiovascular diseases including chronic obstructive pulmonary disease (an umbrella term for lung diseases including chronic bronchitis), heart disease, lung cancer and asthma. Health impact depends on population exposure. Somewhere visibility impairment from NO_x and PM is a subject of control also. Requirements to LAQ are driven by local regulations usually. Significant LAQ pressure exists already - noted 2010 NO_2 EU directive exceeded today at several EU airports [ICAO CAEP/7-IE/WG/3, 2007].

From a scientific and a health point of view – and subsequent policy interest, monitoring and control – the most important pollutants to focus on are nitrogen dioxide (NO_2), regional ozone (O_3) and particulate matter (PM) - currently PM_{10}, $PM_{2.5}$ and ultrafine particles (UFP). Concerning airports, this especially concerns UFP emissions on the apron area (airside) where ramp workers are exposed. The identification of such particles and tackling of their sources remain issues of importance and further investigations. Moreover, appropriate technology and air quality standards, limitations or any other criteria linked to ultrafine particles are still lacking and need to be defined [FORUM-AE, 2015].

FORUM-AE puts an important emphasis on ACARE environmental goals related to aircraft emissions, but sufficient openness is necessary. New topics may emerge, which were not initially shaped. This is the case for instance of: ultra-fine particles (higher LAQ concerns at European airports, perspective of a future nvPM international standard), cruise NOx emissions to be distinguished from LTO NOx, cruise emissions influence on air quality, drop-in kerosene (fossil or renewable) composition optimisation, fuel sulphur content, contrail avoidance strategy, possible CO_2 or non-CO_2 trade-offs with noise environmental constraint, comparison between other transport modes (particles, CO_2), introduction of a new aircraft CO_2 metric from future CAEP standard. Ambient measurements in the vicinity of airports typically show little to no contribution from airport emissions (Zurich Airport, 2013). However, recent studies have shown elevated PM number levels near airports [Hudda et al., 2014; Keuken, et al. 2015]. Measurement protocols and guidelines are established for criteria pollutants. However, the ambient measurement of ultrafine particle number concentrations is not yet standardized.

The estimation of aircraft emissions is particularly difficult, especially as emissions take place above ground level and they therefore represent a three-dimensional source. The ICAO provides information about emissions from specific engine models, within a reference landing and take-off cycle (LTO cycle), which are necessary to compare different engine technologies for certification. However, these emissions figures do not reflect day-to-day conditions, such as weather and the wide range of operational techniques to be employed elsewhere.The ICAO Airport Air Quality Manual [ICAO Document 9889, 2011] provides a number of methodologies, from simple to sophisticated, for estimating aircraft emissions – the more advanced methods being more accurate, but requiring progressively more detailed information as input. In general, both the ICAO "Simple" and "Advanced" methods, result in levels that are likely to overestimate actual emissions and, for the "Simple" method, this can be quite significant.

Figure 4.72 provides a representation of aircraft emissions and how they ultimately contribute to ambient pollutant concentrations that impact public health and welfare. Even from this Figure 4.72 one may conclude on site-specific LAQ in airports. While aircraft emissions can be directly measured at the source and ambient

pollutant concentrations can be measured at any location, modelling is required to attribute the contribution of aircraft to ambient pollutant concentrations [Miake-LyeR., et al. 2016]. Total on-airport emissions are, however, slightly higher, as they include emissions from other sources such as ground equipment as well as airport roads and car parks. There are mostlymoving sources of emission in airports, but the stationary sources like fuel farms and boilers also contribute to local air quality of the airport and its surroundings. The ICAO Manual [ICAO Document 9889, 2011] provides the recommendations to calculate their emission inventory and further dispersion modelling from them to assess the LAQ, so as a wide range of emission reduction programmes, usually implemented through its collaborative approach. But depending on the matter under the control the dominant emission source in airport is an aircraft in operation and maintenance.

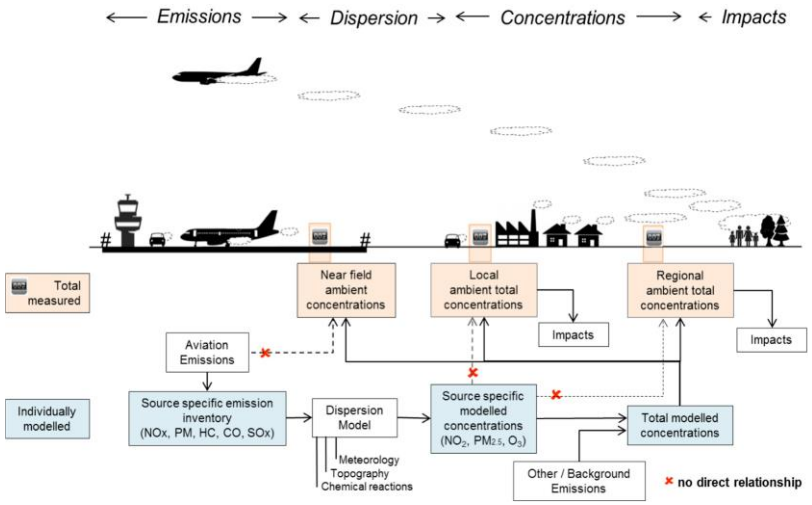


Figure 4.72: Schematic presentation of emissions, dispersion, concentrations and impacts with their interaction at airport level [Miake-Lye R., et al. 2016]

To estimate the ground air pollution in the airport area it is necessary to determine the contribution of aircraft emission at various stages of the takeoff-landing cycle into this process. In the course of aircraft operation, it is extremely difficult to determine from the technical and practical point of view whether it holds the limit allowances of the control parameter – emission. However, there is no need in it, since all stages of engine operation can be reproduced with sufficient accuracy at bench tests.

For instance, International airport Beijing is the second airport in the world as for airport workload. In this research, the emissions of air pollutants from air vehicles and other sources in ZBAA in 2015 were estimated applying the advanced method, which considered the height of the mixed layer computed on the basis of the aircraft meteorological data transponder (AMDAR) instead of applying the height (915 m) recommended by ICAO. Annual emissions of NO_x, CO, VOC_s, SO_2 and $PM_{2.5}$ in the airport made $8{,}76\times10^3$, $4{,}43\times10^3$, $5{,}43\times10^2$, $4{,}8\times10^2$ and $1{,}49\times10^2$ tons per respectively. Spatiotemporal distribution of air vehicle emissions was systematically reviewed to understand the air vehicle emission characteristics. The results showed that NO_x mainly is emitted at stages of takeoff and climbing that makes 20,5 % and 55,5 % of the total emission volume. CO and HC mainly were emitted at taxiing stage that made 91,6 % and 92,2 % of the total emission volume. Since in summer the height of the mixture layer was high, then the emission indices were at the highest level in the year. On the ground of detailed emission calculation, four seasons were imitated applying the model WRF-CMAQ above the space surrounding the airport. The results showed that contribution into $PM_{2.5}$ was relatively high in winter: average deposit made about 115 μg/m^3 in radius 1 km around the airport. Meanwhile, close environs and south-eastern areas of the airport are sensible to $PM_{2.5}$ to the maximum extent. [Xiaowen Yang, et al., 2018].

However, almost all researches related to the estimation of airport cadasters are focused only on emissions of air vehicles, APU and ground auxiliary equipment. Few researches were performed as for other pollution

sources. Moreover, in the majority of those researches, there is employed one of two methods for quantitative estimation of air engine emissions: one applies the cycle of landing and takeoff (LTO) to estimate air vehicle emissions, another uses control values recommended for calculation of ICAO aeroplane emissions (2011). LTO cycle determined by ICAO includes all types of activities near the airport, which take place lower than the height of atmospheric mixture (height 915 m), while the actual mixture height will vary in a different time and in different places. Therefore, those two methods, which estimated the height of the mixture layer to be 915 m will lead to high estimation uncertainty. Detailed and accurate estimations of emissions in airports are necessary to review the characteristics of air pollutants and study of their effect on air quality. From the other hand in spite of the fact that all the more researches pay attention to air vehicle emissions at ground level and air pollution near airports still, there are gaps in such researches, especially in Asian airports.

Air vehicle emissions depended on the following factors: number and type of aeroplanes, types of air engines, fuel used, time spent for each phase of operation, flight power and distance [Song, S.-K., Shon, Z.-H., 2012]. Traditionally researches of air vehicle emissions and their effects can be mainly divided into two parts: emissions of pollutants to atmosphere taking place within LTO phase (local pollutant emissions) and flight phases not related to LTO (i.e. 915 m and at cruise condition level) [ICAO Doc. 9889, 2011]. Aircraft emission effect on human activity at ground level was the most important and all the actions coincided with the airport as for emission sources grew rapidly [Tsilingiridis, G., 2009]. Therefore, there were reviewed air vehicle emissions within LTO phase except for the cruise condition phase. In the emission cadaster, there were applied detailed data on activity provided by ZBAA, including each type of air vehicle, origin and destination point, estimated time of arrival and the actual time of arrival, estimated time of departure and actual time of departure. In this research, the authors used not only improved models to calculate the time of climb and descent, but also the actual time of aircraft taxiing using the information received from the airport (Table 4.14).

In Table 4.16 there are shown emissions of NO_x, CO, VOC_s, SO_2, and $PM_{2.5}$ for the main engines of air vehicles, APU, ground support equipment (GSE), ground access vehicles (GAV), private transport, stationary sources, airport oil depot in 2015. APU emissions are shown in Table 4.17.

In Figure 4.73 there are shown contributions of various emission sources in ZBAA. It's obvious that air vehicle emissions are the most important of all sources an airport, of them, the annual CO, VOC_s, SO_2, and $PM_{2.5}$ made $7{,}56\times10^3$, $3{,}49\times10^3$, $3{,}66\times10^2$, $4{,}6\times10^2$ and $7{,}15\times10^1$ tons per year.

The aircraft was the main airport sources, of them emissions NO_x, CO, VOCs, SO_2 and $PM_{2.5}$ made 86,3 %, 78,7 %,67,4 %, 95,6 %and 48,0 % of the total emission volume respectively. From the review of air vehicle emission characteristic, it was revealed that NO_x mainly is released at takeoff and climb stages that make 20,5% and 55% of the total emission volume (Table 4.18).

Table 3 – Emissions at Beijing Capital International Airport in 2015 (ton/year).

Sources	NO_x	CO	VOCs	SO_2	$PM_{2.5}$
Approach	1.07E+03	2.15E+02	1.52E+01[a]	9.76E+01	2.11E+01
Taxi/idle	7.47E+02	3.19E+03	3.38E+02[a]	1.56E+02	1.41E+01
Take-off	1.55E+03	1.32E+01	2.96E+00[a]	4.56E+01	7.34E+00
Climb	4.20E+03	6.51E+01	1.05E+01[a]	1.61E+02	2.90E+01
Total	7.56E+03	3.49E+03	3.66E+02[a]	4.60E+02	7.15E+01
APU	3.85E+02	1.42E+02	2.12E+01	–	–
GSE	3.41E+02	1.89E+02	5.34E+01	9.70E+00	2.43E+01
GAV	3.71E+02	4.03E+02	5.08E+01	2.05E+00	1.98E+01
Private vehicles	1.65E+01	1.93E+02	1.51E+01	–	1.10E−01
Stationary sources	8.45E+01	1.68E+01	1.37E+01	8.64E+00	8.16E+00
Oil depot	–	–	2.26E+01	–	–
Road fugitive dust	–	–	–	–	2.53E+01
Total	8.76E+03	4.43E+03	5.43E+02	4.80E+02	1.49E+02

[a] Derived from HC using a factor of 1.15.

Table 4.16: Emissions in Beijing airport

Table 2 – Emission factors of auxiliary power units.

Aircraft group	Short-haul	Long-haul
Duration of APU operation	45 min	75 min
NOx	700 g	2400 g
HC	30 g	160 g
CO	310 g	210 g

APU: Auxiliary Power Unit.

Table 4.17: APU emissions

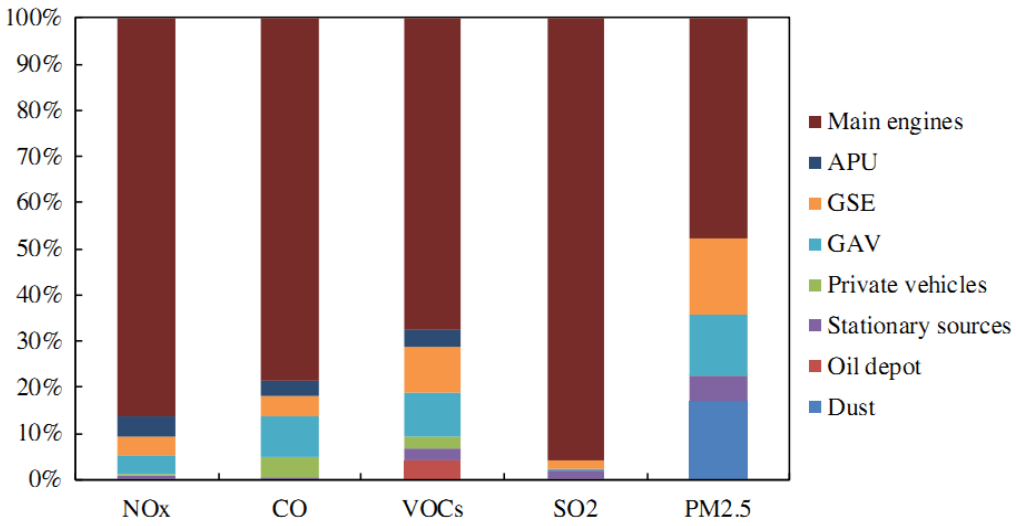


Figure 4.73: Contribution of pollution sources in emissions in international airport Beijing in 2015

Table 4 – Aircraft emissions at Beijing Capital International Airport in 2015 compared with other airports (ton/year).

Airport	Time	LTO cycle	NO_x	CO	HC	SO_2	$PM_{2.5}$	Reference
Beijing	2015	295,100	7.56E+03	3.49E+03	3.18E+02	4.60E+02	7.15E+01	This study
Atlanta	2000	423,423	4.91E+03	5.20E+03	8.81E+02 [a]	4.73E+02	7.00E+01	Unal et al. (2005)
Incheon	2010	214,835	3.65E+03	1.75E+03	2.73E+02 [a]	–	1.82E+01 [b]	Song and Shon (2012)
Gimpo		118,514	7.86E+02	1.04E+03	1.62E+02 [a]	–	7.10E+00 [b]	
Gimhae		62,225	3.32E+02	5.70E+02	9.04E+01 [a]	–	3.50E+00 [b]	
Jeju		103,426	6.00E+02	8.84E+02	1.36E+02 [a]	–	5.90E+00 [b]	
Ataturk	2001	160,901	1.26E+03	2.08E+03	3.72E+02	6.66E+01	–	Kesgin (2006)
Antalya		62,443	4.98E+02	7.73E+02	1.07E+02	2.51E+01	–	
Esenboga		43,364	2.19E+02	3.90E+02	7.33E+01	1.21E+01	–	

[a] Derived from VOC using a factor of $(1.15)^{-1}$.
[b] The emissions of PM.

Table 4.18: Comparative data on emissions in big airports of the world

Taxiing of air vehicles is a considerable source of CO и SO_2 emissions, their share makes 91,6 % and 92,2 % of the total emission volume. The mixing level is higher in summer; therefore, emissions of pollutants in air were at the highest level throughout the year. The ratio of NO_x, CO, HC, SO_2 and $PM_{2.5}$ from air vehicles made 27,2 %, 25,7 %, 25,5 %, 26,9 % and 27,0 % of annual emissions respectively [He, J.-C., and Y.-Q. Xu, 2012].

Chinese air industry had been rapidly growing for the last two decades. Its aircraft turnover had grown by 20% per year [Liu, D., 2010] and the total transport turnover had gained the second place after the USA [Zhou, L.-P., 2010]. At present, the main attention in emission researches is being paid to atmospheric pollutants such as NO_x.

CO_2 emissions from air vehicles had been low in China till the year 1980, while in 1960-1979 they had made 328×10^3 t at average. Starting from the 1980's especially after 1990s CO_2 emissions had been rapidly growing (Figure 4.74). The average growth of CO_2 emissions for air vehicles in China made 826×10^3 tons per year.

The civil aviation in China had been rapidly developing for the recent years and consequences of its emission into atmosphere should not be neglected. Issue of cadasters (accounting) of civil aviation atmospheric pollutants is helpful to associated policy development and contamination control. Fuel consumption and pollutant emissions in China Southern Airline is the biggest national share, each of them makes 27 % and 25…28 % respectively [Weiyi Fan,Yifei Sun,Tianle Zhu,Yi Wen, 2012].

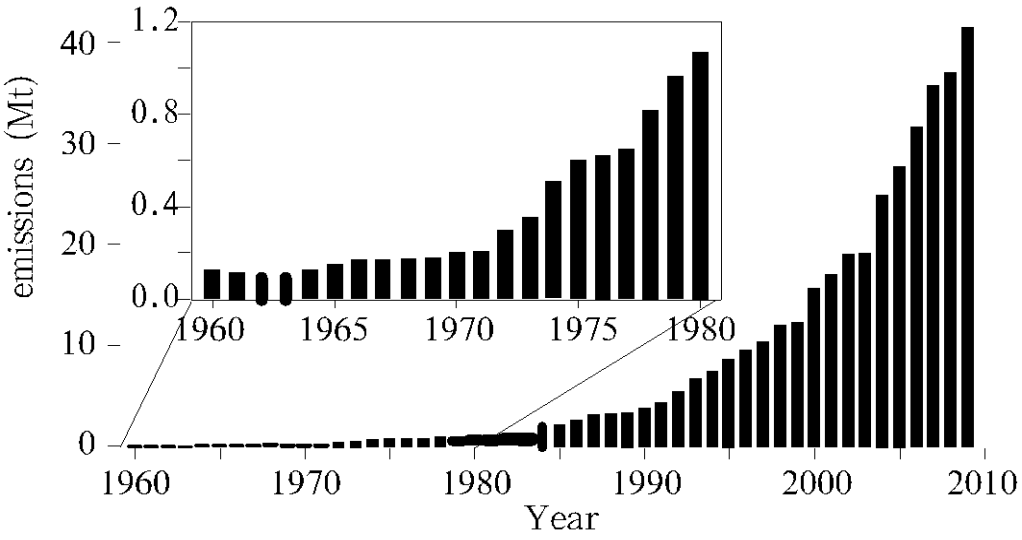


Figure 4.74: Annual CO_2 emissions from civil air vehicles in China within the period 1960-2009

Some of the gaps for the production of airport emission inventories are displayed in the Table 4.19. ACARE's environmental research is driven by five goals to be achieved by 2050. Among them are CO2 emissions per passenger kilometre have been reduced by 75%, NOx emissions by 90% relative to the year 2000. Engine manufacturers, cognizant of aviation's' growing impact on the environment, continue to develop and introduce into service cleaner and more fuel-efficient engines. It must be understood that technology development and introduction of products into revenue service is heavily influenced by customer pull. To address this environmental concern, manufacturers continually work to develop technology for cleaner and more efficient new engine designs, and periodically update existing engines to maintain state of the art durability, performance and emissions.

Source	Activity	Emission factor	Calculation
Aircraft engine	Stop & go behaviour, Idle vs taxi, flex take-off	ICAO Engine Emissions Data Bank, but not yet PM	BFFM2, but FOA for PM
Auxiliary Power Unit (APU)	Environmental Control System Duration	Rudimentary in Doc 9889	Simple product
Aircraft frame	Brakes, tires	Assumptions	Simple product
Ground Support Equipment (GSE)	Machinery good, else poor	EU Non Road Mobile Machinery (EUNRMM)	Simple product
Stationary Sources	Usually well known	EMEP-EEA, manufacturer	Simple product
Landside vehicles	Fair, many assumptions	HBEFA, Coppert, etc.	Simple product

Table 4.19: Level of understanding in airport emission inventory: green (good); yellow (fair); red (poor) (Updated from [Forum-AE, 2015])

Airport emission inventory and air quality modelling improvements are required, which will ask that models more accurately predict concentrations. As illustrated in the previous Table 4.19 there is still a lot for improvement in airport emission inventory making, and that further consolidation is needed in the knowledge of airport emissions sources and their activity (performance), emission factor and calculation algorithm. Linked to both inventory making and air quality modelling, there is a need for further development and validation of performance-based emissions modelling, and the need for harmonisation in this area.

The efforts to reduce (i) noise and emissions, (ii) different types of emissions like CO_2 and NO_x at (iii) local airport or global earth level are not always compatible. A highly efficient engine with low fuel consumption and high speed of the jet exhaust is likely to be noisy. High-temperature combustion to increase thermal and propulsive efficiency increases NO_x emissions. Reducing CO_2 emissions may not lead to the same thermodynamic cycle than reducing NO_x emissions.

In order to improve fuel efficiency, engine pressures and temperatures are increased with time which can lead to higher NOx emissions. As such, following the adoption of the original emissions standards, more stringent NOx limits have been periodically introduced in order to mitigate the potential trade-off with market-driven fuel burn improvements. The NOx limits are referred to by the CAEP meeting number at which they were agreed (i.e. CAEP/2, CAEP/4, CAEP/6 and CAEP/8). The regulatory limits for smoke, HC and CO have not changed from their original value as they are considered to provide adequate environmental protection. These regulatory limits provide a design space for aircraft engine technology within which both NOx emissions and fuel burn can be reduced.

Latest advances in engine combustor design technologies were considered in the context of the existing mid- and long- term CAEP goals. To provide the latest state of technology, currently, CAEP is working on an

integrated independent expert technology goals assessment and review for engines and aircraft which aims to be delivered to the CAEP/11 meeting in February 2019 [ICAO Secretariat].

A certification Standard to control the amount of oxides of nitrogen NO_x permitted to be produced by civil turbojet and turbo-fan aircraft engines was first adopted by ICAO in 1981. The stringency of that Standard was successively increased at ICAO CAEP/2, 4, 6 meetings and most recently at CAEP/8 in 2010. The introduction of a standard to control NO_x production was originally driven by concerns relating to surface air quality where NO_x is implicated in the production of ozone in the vicinity of airports.

To complement the Standard-setting process, CAEP agreed in 2001 to pursue the establishment of technology goals over the medium and long term. These were to be challenging yet achievable targets for researchers and industry to aim at, in cooperation with ICAO Member States. Also, they provide policymakers with a view of what technology could be expected to deliver emission reductions in the future. The first of these reviews was to focus on NO_x and to help achieve this, a panel of Independent Experts (IEs) was appointed and tasked with:

- Leading a review of technologies for the control of NO_x.
- Recommending technology goals for NOx reduction from aircraft engine technologies over the 10 years' and 20 years' time horizons.

The goals can be seen in Figure 4.75, which is taken from the 2006 report of the IEs, together with goals proposed by the EU ACARE and the US Ultra-Efficient Engine Technology (UEET). It is important to note that these other goals were not used to influence the CAEP goals and were plotted simply for comparison. The graph also illustrates the historic ICAO NO_x Standards and highlights the large gap between the goals and the latest standard. It is important to note that the goals indicate that significant NO_x reductions are achievable over the 10 and 20-year timescales based on the leading edge of control technologies; while standards, on the other hand, are based on already certified technology.

Figure 4.75 also illustrates the continuous improvement achieved over time with newly certified engines achieving the largest margin to the limits. Some of the engines certified since 2008 are already close to mid-term and long-term technology goals. Figure 4.76 illustrates the evolution of the average margin to the CAEP/6 NO_X limit for EASA certified in-production engine models. During the last five years, the margin has increased by approximately 3% per year. It is noted however that the trend is influenced by which engines go out of production, and whether the new entries in the ICAO Aircraft Engine Emissions Databank represent new engines or derived versions of existing engines with smaller evolutionary improvements.

Figure 4.75 uses the recognized NO_x certification metrics and shows the amount of NO_x produced from an LTO cycle (Figure 4.77) on the vertical axis (grams per kN of thrust), and the engine overall pressure ratio (OPR) at the take-off condition on the horizontal axis. It is evident that the larger, higher thrust engines operating at higher pressure ratios, and consequently at higher thermal efficiencies, produce greater amounts of NO_x. In relation to the degree of uncertainty, it should be noted that the bandwidth was greater for a longer time period. The medium-term goal for 2016 was agreed at 45% ± 2.5% below CAEP/6 at OPR 30, and the long term goal for 2026 at 60% ± 5% below CAEP/6 also at OPR 30.

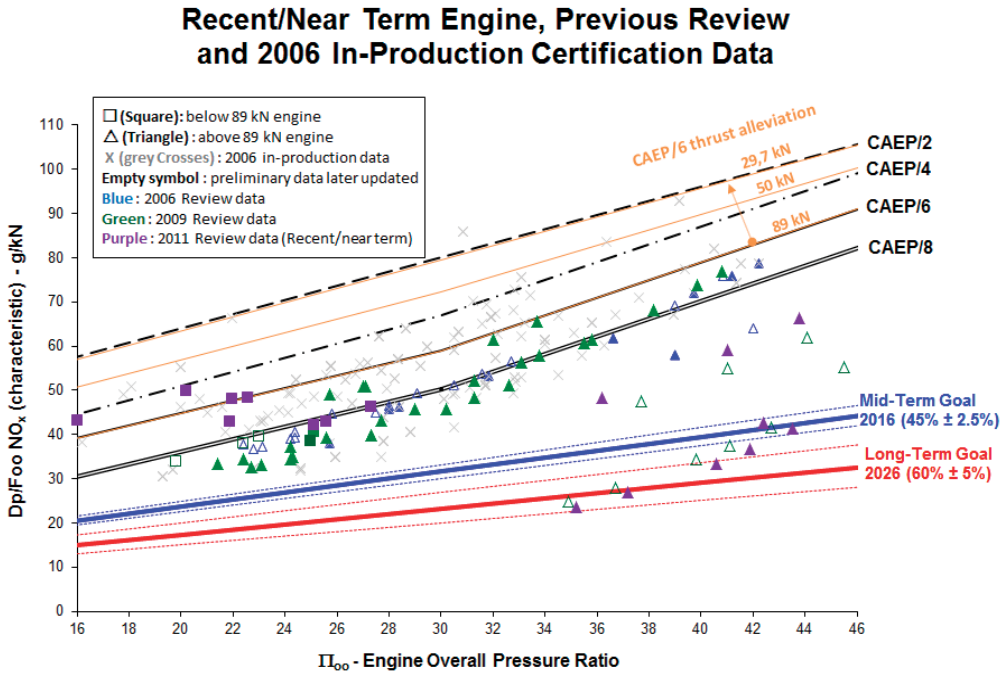


Figure 4.75: Historical ICAO certification Standards together with the 2006 medium-term and long-term goals

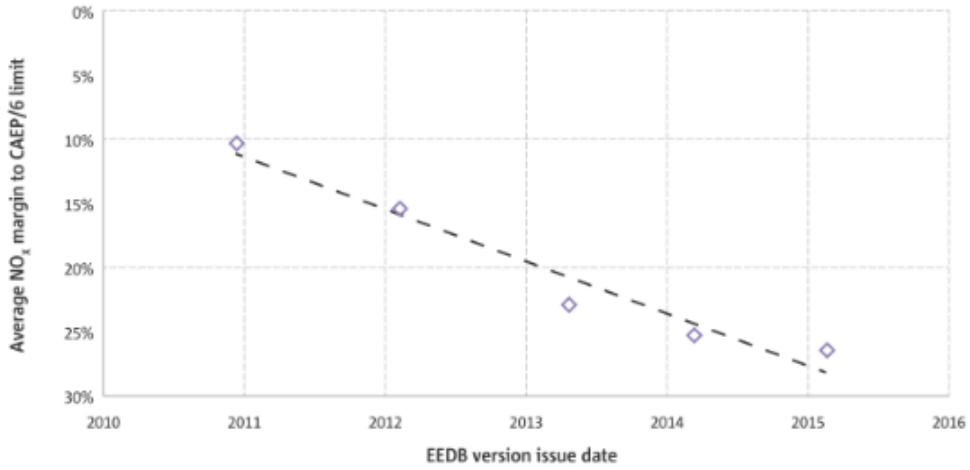


Figure 4.76: Improving average NOx margin to CAEP/6 limit for in-production engines shown in successive versions of the ICAO EEDB

The second CAEP IE review for NO_x emission [ICAO, Doc 9963, 2010] was intended to be less extensive and was focused on what had changed in the intervening three years since the first review. The IEs concluded that the scientific evidence supports continued efforts to reduce aircraft NO_x emissions and that the evidence of the impact of aircraft NO_x on both surface air quality and global climate change was, if anything, more compelling than during the first review. Nevertheless, given the still considerable uncertainty about the quantification of these impacts, the IEs recommended continued research on NO_x emissions, and other emerging concerns such as particulate matter (PM), and the role of NO_x in PM formation. As in the 2006 report, it was again concluded that for SAQ, NO_x continues to be an important pollutant and in the context of Global Climate Change (GCC) its ranking versus CO_2 continues to depend crucially on the length of the time horizon. It appears that NO_x is more important in shorter time periods, with CO_2 dominating in the longer term, and then continuing to do so over many hundreds of years.

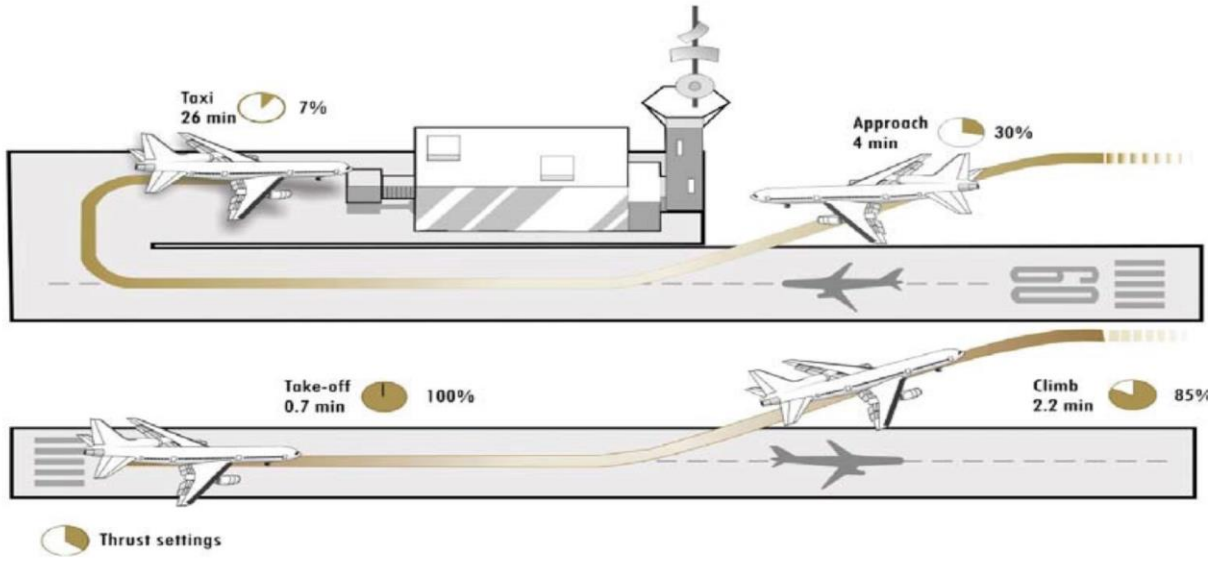


Figure 4.77: Illustration of ICAO emissions certification procedure in the LTO cycle

Since 2006, further significant reductions in NO_x emissions have been evident, something for which manufacturers should be congratulated. Advanced combustors can be categorized into two broad types: RQL systems (rich burn, quick quench, lean-burn), and staged-DLI (direct lean injection), also called staged lean-burn systems. In very simple terms, RQL combustors control NO_x production through a series of changes to the air to fuel ratio as the combustion air progresses through the combustor. Staged-DLI combustors operate quite differently with NOx control being achieved by switching (staging) between the pilot and main burner zones arranged in concentric circles. Although reductions in NOx production were shown to have been achieved by both types of combustor, neither was deemed to have met the goals set at the first review - defined as having reached Technology Readiness Level 8 (TRL8)- although they were possibly close to that.

The Figure 4.78 provides a summary presentation of the test data results received for this review with the two types of combustor identified separately; the data points coloured grey being for RQL combustors and those in red being for the new staged-DLI combustors. As with the first review, the conclusion reached was that RQL combustors appear likely to meet the MT goal, though a significant challenge remains, the LT goal may not be achievable particularly for high OPR engines. Dramatic reductions in NO_x production from the use of new generation staged DLI combustors were in line with the expectations recorded in the 2006 Report, although the migration towards the LT goal was not expected so soon. However, the widespread of NO_x performance raised questions about how such families of engines might be handled in the future within a goal setting process.

Information presented for advanced RQL combustors was believed not to challenge the definition, or levels, of the goals established at the first review. The somewhat limited information relating to the new generation staged-DLI combustors, however, was thought to offer something of a challenge to both the definition and the goal levels. Nevertheless, since they are untested in commercial service, the IEs decided not to change the goals at this review but to wait until further experience had been gained. It was concluded that staged-DLI combustors were likely to be essential to meet the LT goal, particularly at high OPRs. A critical factor for future goal setting will be the extent to which advanced RQL and staged-DLI systems can be made to work effectively for (smaller) low and mid-OPR engines.

The objectives of the European programs are to reduce short- & long-term development costs, incorporate new technology faster into future products and improve the environmental impact with regards to emissions. Specific goals of the EC FP6 Aeronautics Work Programme are to reduce NOx emissions over the ICAO-LTO

cycle by 80% compared to the CAEP/2 standard and achieve a NOx emission index of 5 g/kg at cruise [ICAO CAEP/8-IP/11, 2010].

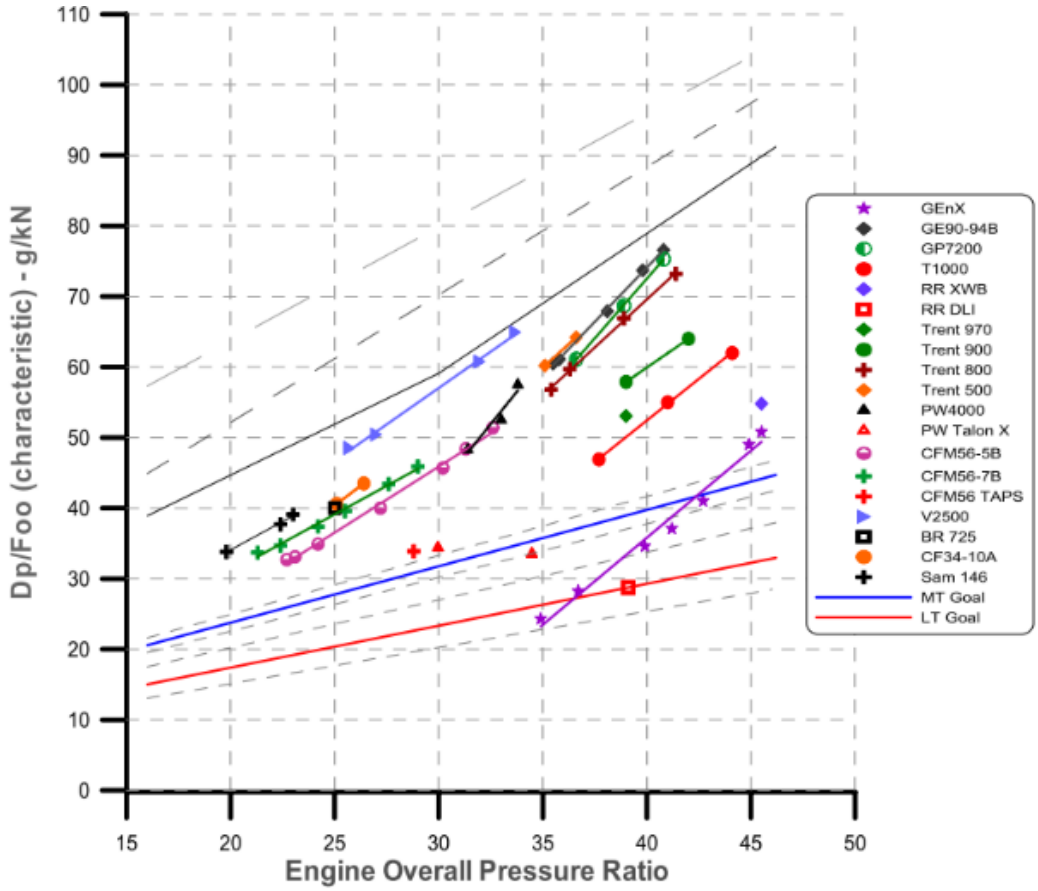


Figure 4.78: 2009 Review data with RQL combustors in grey and new mid-OPR engines. Generation staged DLI combustors in red. Note these data points area mixture of certificated engines and high TRL developments

Good progress has been shown on state-of-the-art Single Annular Combustors with rich burn (air blast) injection, Double Annular Combustors/Axially Staged Combustors (rich pilot / rich main) and Lean Burn Combustors. The latest state-of-the-art lean burn fuel injection systems with centrally integrated pilot fuel injection for flame stabilisation have achieved up to 70 to 75% of NO_x reduction at TRL3 (demonstrated in a high-pressure single sector combustor test rig) relative to the CAEP/2 certification standard. A technology deterioration factor, which describes the transition from TRL3 to TRL6 needs to be considered, leading to likely technological progress by the end of Framework 7 of a range of approximately 60 to 65% NO_x reduction. It is most likely that in Framework 8, research initiatives will need to focus on further improvements towards 70 to 85% NO_x reduction, which may lead to another 50% relative NO_x reduction and higher Technology Readiness Levels [ICAO CAEP/8-IP/11, 2010].

Lessons learned from the example of technology transition are: that the technology transition process is complex and expensive, and may not progress in a predictable fashion; commitment of a new technology to product requires a solid technology foundation (complete TRL 6 demonstration), understanding of environmental benefits and trade-offs, a clear customer need, and enabling technologies (e.g. digital control and fuel nozzle protection technologies); initial research goals tend to overestimate benefits because the environmental benefit relative to evolving current technologies tends to decrease with time and the time required to complete product transition tends to exceed initial estimates; and technology transition is not

complete at certification (TRL8). Product upgrades continue to cover more engine models and improve combustor performance after TRL8 [ICAO CAEP/8-IP/11, 2010].

One should pay attention to the fact that results of the research of the aviation emission effect on climate [Gettelman A., et al., 2017] show that it is necessary to introduce additional normalization for NO_x emission level in the high-level atmosphere. In the high troposphere, at a height about 10-11 km, where cruise flights of passenger aircraft and air-freighters take place the main effect of aviation emission is exercised through the change of planet thermal balance as a result of greenhouse effect growth and reduction in atmosphere transparency. At present ICAO interacting with other international environmental organizations has determined the technological target level of NO_x emissions in high-level atmosphere (9-13 km) for subsonic aircraft - $EINO_x$=5 g/1 kg of fuel.

In the work [Volkov S.A, Gorbatko AA, Khaletsky Y.D., 2010] the authors state the estimated value of the regulatory restriction to NO_x emission at level $EINO_x$=5 g/1 kg of fuel (at the first step of the restriction introduction it is supposed that the index is set at level $EINO_x$=10 g/1 kg of fuel).

The authors [Volkov S.A, Gorbatko AA, Khaletsky Y.D., 2010] mark that achievement of the technical level stated at simultaneous satisfaction of ICAO prospective allowances for NO_x emission at the condition of LTO cycle is a complicated scientific and technical problem.

Should we compare the aircraft designed to provide high cruise efficiency and low global emissions (a) and the aircraft designed to provide low noise and emission level near airports at takeoff and landing (b), then they can differ very much. The aim (b) leads to the fuselage similar to the aeroplane with a wide-span wing and an engine with slow cold exhaust to provide low engine and aerodynamic noise and emissions. Such configuration has low cruise speed and small efficiency that leads to flight time increment and excessive fuel consumption as well to the cruise flight emission level. Vice versa aim (a) leads to the aeroplane with a sweptback wing and high gas speed from a jet engine to provide high cruise speed and small fuel consumption and emission level. But in doing so the noise level near airports will be higher, the emission level also will be higher due to higher flight speed and exhaust velocity at takeoff and landing.

Plenty of engines and noise sources, as well as compatibility of CO_2 and NO_x low emission levels at local and global levels, is that immense set of limitations directed to the protection of environment and aims, which can require major changes:

- engines with a variable cycle, high speed of jet stream at cruise flight condition as well as low speed of exhaust jet at takeoff and landing;
- new aircraft configurations, for example, flying wing, joined wing, v-tail or U-tail with noise shielding and/or buried engines.

It will be required that those designs meet version (a) with more than ever strict environment protection allowances and be compatible with (b) improved efficiency and saving. Since both of those factors provide continuation of air traffic growth together with its mobility.

Improvement of engine efficiency can be achieved for new types of air vehicles as well as for those being in operation. For example, long-term programmes on engine renewal for the recent decade led to reduction of oil consumption by 2%. It is estimated that new engine technologies such as coating materials, combustion chamber technologies, sensors and cooling technologies will permit the engines and auxiliary power units of new aeroplanes to save 15% of fuel compared to the previous generation of air vehicles.

In the long-term prospects, there are reviewed radical changes in the engine design, for example, engines with an open rotor. If noise and vibration problems can be solved, then engines with an open rotor will potentially improve fuel saving [Lee, D.S., et al., 2009; King, D., et al., 2010].

In the work [Hendricks, E.S., Tong, M.T. 2012] the results of imitation for the engine with an open rotor were compared with similar results of imitation for turbofan engines with a drive either through a reduction gear or with a direct drive. It is supposed that the system with an open rotor will have higher specific oil consumption compared to both types of turbofan engines. At the same time, direct comparison of engines with an open rotor and turbofans with a direct drive and the drive through a reduction gear can give some notion on the advantages of each of them. Engine effect can be assessed only in the course of their integration in an air vehicle in general. When integrating an engine into an air vehicle, one can make a general estimation of fuel consumption, exhaust (emissions) and noise. In the work [Hendricks, E.S., Tong, M.T. 2012] the engine with an open rotor was integrated into the prospective aeroplane in order to assess the potential win from the application of engines of such type. In general, it is anticipated that aeroplanes with an open rotor will have fuel consumption by 36% lower than the main air vehicles of the 1990's. Moreover, as for estimations, the aeroplane with an open rotor has a 13-fold margin by the cumulative noise level of chapter 4 [Guynn, M., 2012]. Although there is uncertainty in both those estimations, the data show that the engine with an open rotor can meet future requirements for aeroplanes.

Demonstrator Open Rotor (Figure 4.79) designed in the framework of immense research programme Clean Sky in Europe is a strategic direction of SAFRAN RESEARCH&TECHNOLOGY efforts and is a key part of SAFRAN plans on the design of the power plant meeting future needs of aircraft manufacturers till the year 2030.

As it's clear from the name, Open Rotor has a breakthrough architecture with two counter-rotating self-sustained fans that permit them to reduce fuel consumption and CO_2 emissions by 30% compared to modern engines of type CFM56. The demonstration program launched in 2008 and managed by SAFRAN reached several important stages including tests of an air tunnel in French aerospace research agency ONERA. It led to the assembly of a demonstrator in 2015 and starting of open-air ground tests. SAFRAN also studies other engine solutions in particular UHBR (Ultra High Bypass Ratio) – turbofan engine with ultra-high bypass ratio that will reduce fuel consumption by 5-10%.UHBR will become a reliable solution for aircraft manufacturers by the year 2025 as it can be easily integrated into modern aeroplanes. At the same time, SAFRAN also studies distributed electrical and hybrid engine systems.

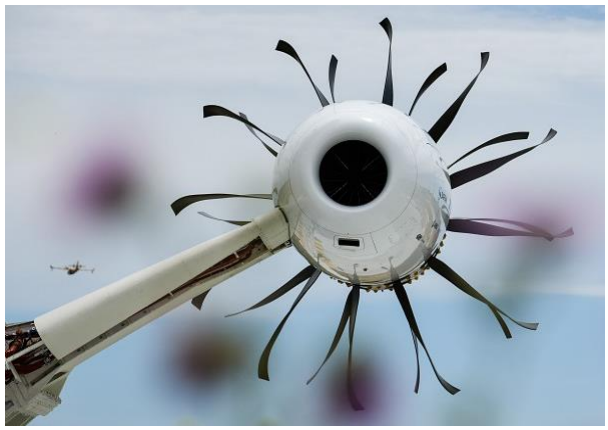


Figure 4.79: Demonstrator SAFRAN "open rotor"

NASA project "Environmentally Responsible Aviation" (ERA) with industry involvement develops technologies of fuel combustion for low-emission combustion chambers of the new generation to meet the requirements of the target level 2020. Prospective combustion chambers will reduce emissions of nitrogen oxide (NO_x) by more than half from the emission level of the existing combustion chambers reducing simultaneously the noise level and specific fuel consumption. In 2012 at NASA ASCR test bench there were determined emission characteristics of two technologies of fuel combustion - PW ACS and GE TAPS. The

measurement results showed a considerable reduction of NO_x emissions by 75% lower than CAEP 6 2004 level [Chang CT, Lee CM, Herbon JT, Kramer SK, 2013].

As the level of NO_x emissions is an integral index to be determined by the speed of nitrogen oxide formation, which depends exponentially on gas temperature, then the level of NO_x emissions is well correlated with fuel injector characteristics determining the degree of fuel-air mix preparation. The fastest and uniform agitation of fuel with air before combustion –a key technology for provision of low-emission combustion. The main difficulty in a solution for this problem is the necessity to prepare well agitated fuel-air mix within the time, which is reduced at temperature and gas pressure rise due to enhanced probability of self-ignition and flashback.

The existing trends of increase in pressure rise degree advance extra requirements for combustion chambers including the capability to operate at higher temperatures. Applications of ceramic composite materials and thermal protection coating are additional technologies providing new capabilities of combustion chambers. The flame tube made of ceramic composite materials can withstand temperatures higher than the traditional one made of super-alloyed material thus not requiring lower air consumption for cooling. The application of those materials makes possible to employ extra air in the fuel nozzle to increase fuel and oil agitation. It provides more homogeneous mixture with a smaller number of local hot spots that in turn permits reduction of air volume for cooling of the flame tube. Thermal protection coating protects the surface of parts made of ceramic composites from oxidizing and reduce temperature mode of the flame tube and extend the service life of the product.

Starting from the traditional design Twin Annular Premixing Swirler (TAPS) made with the employment of several technological and commercial programmes including GEnx and LEAP (Figure 4.80), GE company has extended possibilities of that technology to reach the aims of N+2 generation on NO_x and efficiency. Architecture, scale and cycle of the engine were set using the review of engine-aircraft system pointing at the concept of aircraft and engine Hybrid Wing Body (HWB), which might meet the key aims of the generation as for NO_x level, specific fuel consumption and noise reduction. The main concept of GE combustion chamber design of N+2 generation is an increase in air share employed for preliminary agitation in the combustor flame tube head (higher 70%). Moreover, there are employed structural elements, which improve heat-air mixability. Increase in air volume for preliminary agitation can lead to a breakdown of difficulties coincided with either provision of serviceability (combustion efficiency and combustion stability) or structural durability (due to reduction of cooling air consumption).

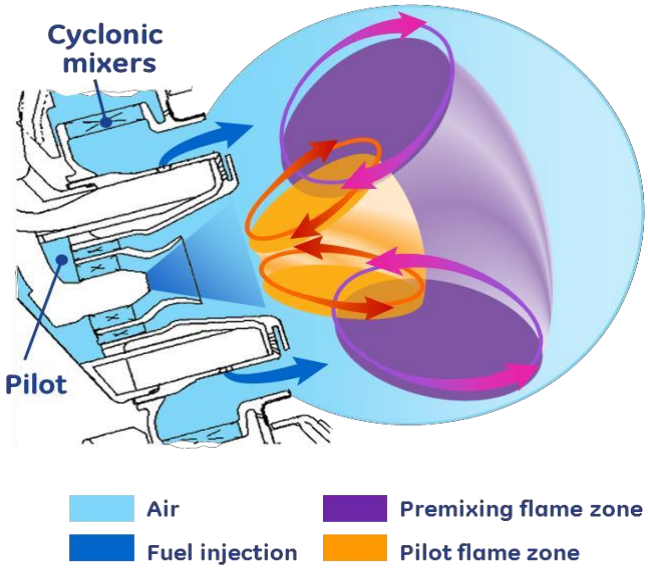


Figure 4.80: Concept of TAPS dilution section

In the framework of researches by the ERA project, new technologies of fuel combustion were compared to the results obtained in previous successful programmes on technology advance for combustion chambers. Tests were performed at NASA installation in the whole range of operating parameter variation. [Chang CT, Lee CM, Herbon JT, Kramer SK., 2013]

On the basis of result review of emission characteristic experimental determination 3 most prospective versions (of 13 versions under research) were selected and then further design optimization was made, after that one final structural version of the combustion chamber was tested by NASA new five-head section (Figure 4.81) [Herbon J., et al., 2017].

By results of NO_x emission level experimental determination in 5-head section the GE combustion chamber provides the level meeting 19% NO_x from CAEP6 regulatory requirements at target level for the engines of N+2 generation meeting 25% from CAEP6 regulatory requirements at good combustion efficiency and acceptable level of pressure fluctuations at this design stage (Table 4.20). Further development of that technology will be focused upon the thermal state, mechanical strength, processibility and design optimization in order to find a compromise between the provision of fuel combustion efficiency and pressure fluctuation level in the combustion chamber from one side and NO_x emission level per LTO cycle.

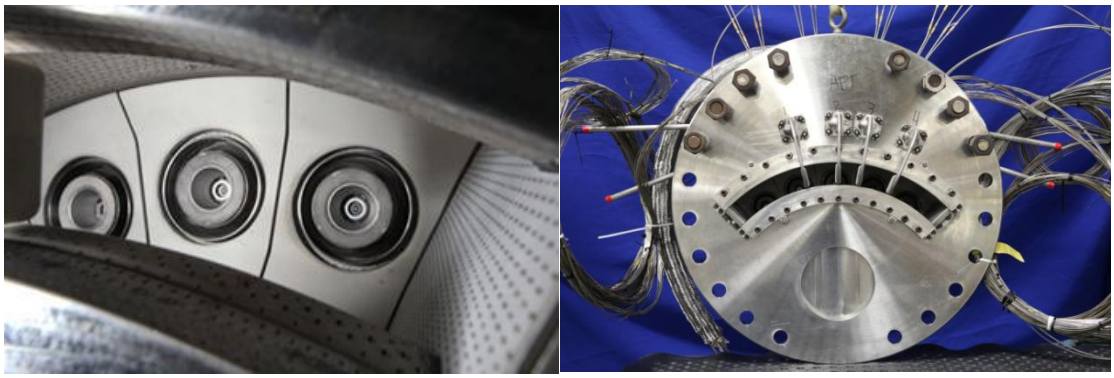


Figure 4.81: Combustion chamber 5-sectional sector

TAPS design permitted them to combine two combustion areas in a single volume of the flame tube: rich one implementing the diffusion combustion pattern and weak one – with the combustion of the well-premixed practically homogeneous fuel-air mix. In TAPS combustion chamber two high-power swirlers are located around the central nozzle. Thus, it is achieved a reduction of concentration fluctuation and combustion product temperature (approximately by 50%). Due to this combustion efficiency is improved and the NO_x emission level is reduced. One radial swirler is located on the fringes; fuel is supplied by 12 pneumatic nozzles to the airflow swirled by it. Premixed and vaporized lean air-fuel mixture enters the chamber and is combusted as almost homogeneous one. The application of such an approach makes the major contribution in NO_x emission reduction since minimum half of all fuel is combusted in this area.

% ICAO	$EINO_x$	EICO	EIHC
100	17,62	0.20	0.01
85	7.89	0.05	0.01
30	11.75	3.13	0.05
7	5.18	28.44	2.13
% CAEP 6:	18.9 %	20.4 %	8.8 %

Table 4.20: NO_x emission level of GE 5-head section for ICAO LTO cycle

P&W company in the framework of the EA project has demonstrated several very diverse concepts including also the improved version of its TALON X combustion chamber with rich combustion. Final conception version on Axially Controlled Stoichiometry (ACS) of the combustion chamber was selected for NASA tests that considerably improved its characteristics compared to those achieved two decades ago. ACS concept was preliminary tested in three-sectional sector at UTRC installation, then it passed NASA tests at ASCR object (Figure 4.82).

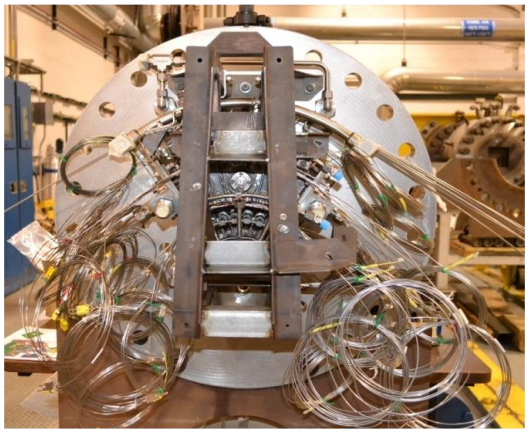


Figure 4.82: Three-sectional sector of low-emission combustion chamber at NASA ASCR bench (Pratt & Whitney)

By NO_x emission level experimental determination results P&W ACS combustion chamber provides the level meeting 12% NO_x from the regulatory requirements CAEP6 at combustion completeness minimum 99,9% at maximum rating. As it is clear from the above mentioned, P&W together with United Technologies Research Centre (UTRC) to achieve the aims of NASA programme have successfully applied the approach containing reprocessing of the family concept studied earlier and have assessed probable potential on emission abatement and operability improvement.The concept changes under consideration included the application of multi-point lean flame tube heads, radial swirlers, axial zoned combustion chambers and combustion chambers with rich-quench-lean (RQL) mixture. P&W company have attained considerable improvements in TALON X Rich-Quench-Lean and continues development for additional emission abatement.

The concept of multipoint injection has a drawback – big number of injection points. Modern manufacturing technologies reduced the production cost of the multi-point combustion chamber. However, it is required for developing the activities, which will avoid the probability of fuel channel carbonization. It was expedient to reduce the number of injection points thus providing high efficiency of fuel-air agitation [Chang CT, Lee CM, Herbon JT, Kramer SK, 2013].

Both combustion chamber concepts from GE and P&W have surpassed the target level for engines of N+2 generation meeting the level 25% from the allowance of CAEP-6 LTO NO_x at good combustion efficiency and pressure fluctuation at level TRL 4. Both combustion chamber conceptions researched to meet the requirement on NO_x emission abatement level at cruise condition by 70% as well as considerably reduce the volume of hard particles emissions that is important for the chemical composition of the upper atmosphere.

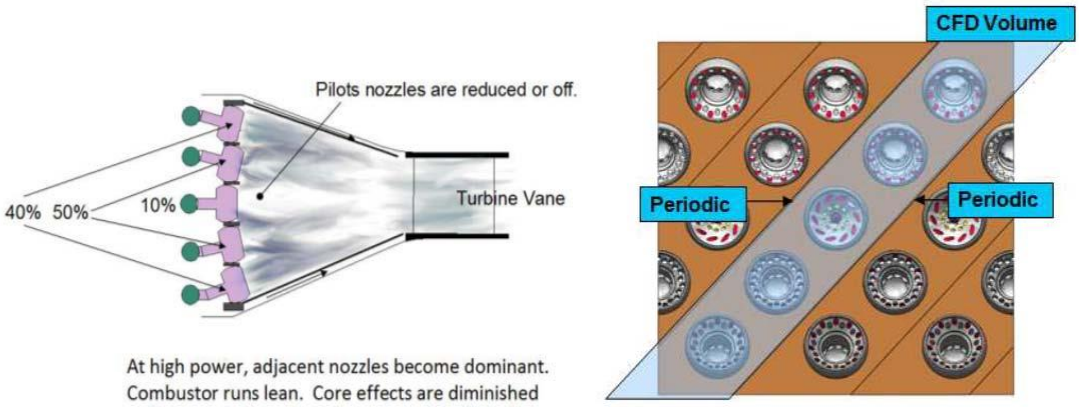
The degree of influence of nozzle recession and dilution section on operating and emission characteristics was estimated in the course of a detailed study of the scheme characteristics for LDI fuel combustion technology. Goodrich, Woodward and Parker have obtained excellent results in combustion chamber testing within mid-pressure range demonstrating ignition, flame propagation and NO_x emission abatement.

NASA plans to continue tests of those concepts at the mid-pressure installation to estimate their capability in ensuring NO_x emission abatement.

Goodrich (at present called UTC Aerospace Systems) has developed a modular LDI array around discrete-jet based air-blast fuel nozzles (Figure 4.83a). Intense mix turbulence level is produced close to the fuel injection

point. As a result, it is obtained rapid breakup of fuel and vaporization sheet accelerating the process of homogeneous combustible mixture formation especially, at low engine power setting.

Rows of slightly recessed pilot nozzles, designed to ensure secure ignition, are dispensed in the multiple-stage matrix (Figure 4.83). Air flows through the pilot nozzles makes 10% of the total air consumption and fuel is dosed independently of the supply to the major elements. It is anticipated that employment of separately prepared areas of the fuel-air mixture will permit them to minimize NO_x emissions thus providing a wide range of combustion chamber steady operation.



a) b)

Figure 4.83: Goodrich multi-zone multi-stage LDI concept

At present, the researches were continued to determine the optimum design of the nozzle jet, which further will be tested at the maximum pressure mode. There were performed tests to determine the emission level of that fuel consumption technology employing Jet-A fuel and alternative fuel at low-pressure modes; at present it has been planned to perform tests at middle and high-pressure modes in NASA to confirm efficiency of LDI multi-point scheme in order to abate NO_x emission level [Prociw, A., Ryon, J.,Goeke J., 2012].

Woodward FST based their developed concept on combined types of fuel nozzles by the simple vortex and shear action. Their LDI package module consists of multi-stage series of smaller and more compact nozzles surrounding the central bigger module, which provides low-power operations. Modules can be added together as a multi-component sector (Figure 4.84). The built-in module provides a zoned effect and shields from its neighbours. At low power settings, the fuel-air mix distributed uniformly can be excessively lean to burn.As a result, it is used a multi-stage fuel-feeding scheme to ensure the combustive composition of the mixture at very low total equivalence numbers. In Figure 4.85 it is shown 5-burner annular compartment during the test to determine the margin for a lean blowout. At present, the works on the maturation of the fuel preparation system are underway [Lee, Ph., 2012].

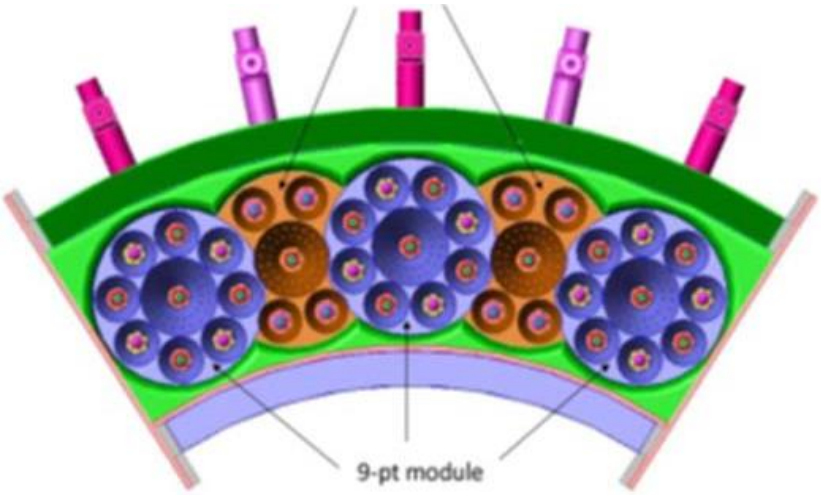


Figure 4.84: Woodward LDI package in 5-sectional sector

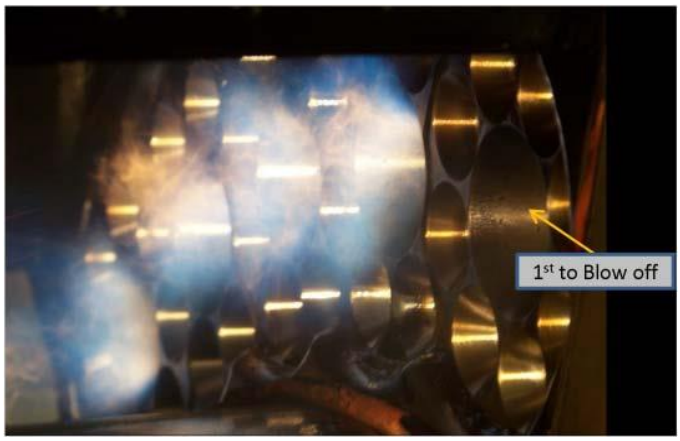


Figure 4.85: LDI Woodward package undergoes tests with lean mixture

Parker [Parker R., Lathoud M., 2010] presented the version of multi-stage 3-zone injector module designed under UEET NASA programme. The concept originated from the idea of updating CC modern injectors applying new equipment having the improved characteristics (Figure 4.86). The module is composed of miniature mixing cups each fueled by a pressure-swirl nozzle. The cups are formed using Parker's platelet technology and produce intense turbulence when the fuel injection takes place. Three zones are formed by canting the side nozzles away from the middle layer to provide some relief from injector interaction.

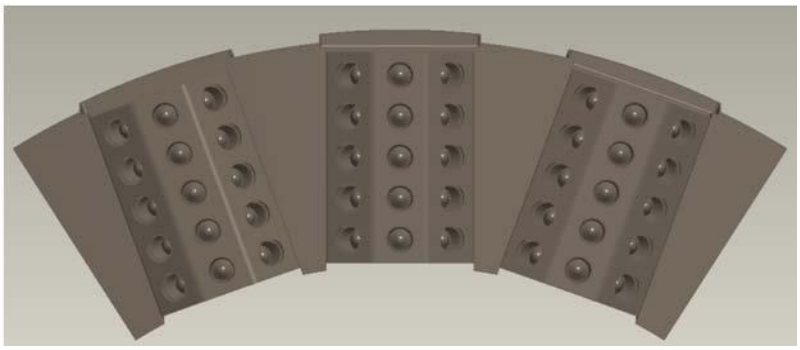


Figure 4.86: Conceptual implementation of 3-zone module

Multiple fuel stages are used to shift fuel spatially to provide the leanest and acceptably-stable burnable fuel-air mixture (Figure 4.87). This package passed tests at middle power conditions and is accepted for testing under high pressure in NASA [Lee, C-M., Chang, C., Kramer, S., and Herbon, J., 2013]

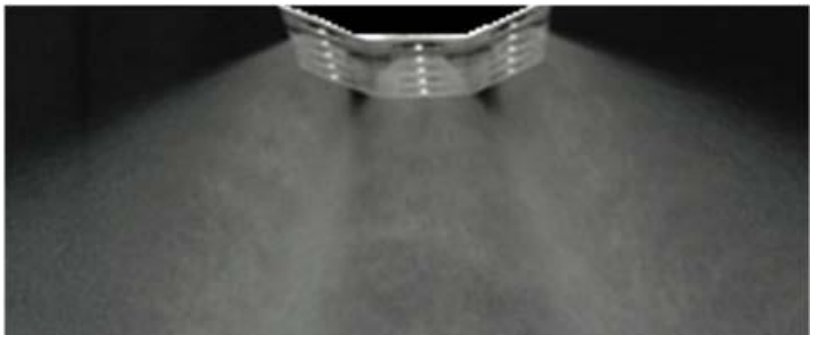


Figure 4.87: Spray test using Parker 3-zone probe

Bypass turbojet Trent 1000 was produced basing on bypass turbojet Trent 900 applying new technical solutions from the prospective technology solution program Vision of company Rolls-Royce [Madden P., 2005; Haley Ph., 2006]. The design features of the engine are as follows:

- single-step low-noise slow-speed fan, diameter D_F=2,845 m with 20 wide-chord light impeller blades made of titanium alloy with variable-sweep by height and improved aerodynamic characteristics as well as the small relative diameter of the hub;
- intermediate pressure power off-take, two N_{st}=250 kVAstarter-generators are installed on, ensuring engine starting and electric power supply to aircraft systems;
- new nickel alloys, HPC and LPT blade manufacturing technologies providing engine life extension;
- low-emission one-layered annular combustor of "plate" design with direct fuel injection and lean combustion zone;
- counter-rotating rotors of high and middle pressure;
- anti-icing system at Middle-Pressure Spool inlet;
- smart transmitters in ACS and technical condition diagnostic system.

The application of the fan with a hub of small relative diameter in bypass turbojet Trent 1000 ensures a reduction in weight, outer resistance and oil consumption. The applied design of fan impeller blades provides little weight, good aerodynamic characteristics and rigidity to ingestion. Outlet guide vanes also have light sweepback vanes; the technological process used for their manufacture is similar to impeller blades.

To reduce the noise level in the bypass turbojet Trent 1000 and Trent 900 there have employed the following technical solutions: new fan casing with an inner circuit, reducing the noise level in the source; the optimized number of sweepback vanes in the outlet guide vanes; slow-speed fan with sweep variable by height; acoustic treatment of LPT casing.

The application of the intermediate pressure power off-take in the bypass turbojet Trent 1000 used for engine starting and electric power supply to aircraft systems makes possible to:

- reduce short-haul fuel consumption by 6% and specific fuel consumption at cruise condition by 1…1,25 % relatively to the engine with HPC power offtake;

- reduce thrust at a ground idle condition that favourably affects the reduction in fuel consumption, noise as well as the load on landing gear wheel brakes;

- reduce the time of the transient process from idle condition to the maximum one owing to abig margin of HPC gas-dynamic stability;

- increase HPC gas-dynamic stability margin;

- curtail operating costs.

In the bypass turbojet Trent 1000 due to the fluid drive coupling applied in intermediate pressure power off-take at engine starting by the starter, both rotors – middle-pressure spool and HPC are spun with the result that the starting time is shorter than 40 s [*Aviation Week, 8/V, 2006, v. 164, №9, p.48-50*]. At flight conditions, the power off-take for the generator drive is made mechanically from the middle-pressure shaft. Generators of each engine can produce up to 0,5 MW of electric power for B787 electrical systems.

High pressure and temperature of the combustor led to an undesirable increase in NO_x emissions. The rate of NO_x formation grows with the temperature rise in the combustion area reaching the maximum values at ratio air-fuel close to stoichiometric one. Consequently, to provide a low level of NO_x emissions the time spent for mixture combustion at high temperatures shall be minimized. The example of implementation of such approach providing the margin as for harmful substance emissions relative to the ICAO regulatory requirements serves the combined technology Rolls-Royce "Phase 5" employed in Trent engine series [Parker R., Lathoud M., 2010].

The extension of electrical technology application in further aeroplanes and engines will be helpful. Aircraft and engine systems traditionally represent the aggregate of hydraulic and pneumatic systems. Many of them, for example, air conditioning systems (in the cabin), driven by compressed air to be supplied directly from engine compressors can be replaced by special lighter and more power-efficient electric equipment. The engines can produce high electrical load, for example by embedded electrical generators. Sustained control over this electrical load also can offer opportunities to improve the engine. "MOET EU" programme is directed to the integration of completely electrical aeroplanes and engine systems. It will provide a reduction in fuel consumption by 2% together with all operational advantages: maintenance and reliability [Parker R., Lathoud M., 2010].

In the work [Zhoujie Lyu, Martins J.R.R.A., 2015] the trailing edge was optimized with various conditions throughout the whole flight as for the company plans. The authors observed a 1% drag reduction at design conditions and 5% drag reduction out of design conditions. The efficiency of trailing edge morphing is demonstrated by comparison with optimized results of the hypothetic, completely morphing wing. Moreover, it was computed the reduction in fuel consumption for several flights applying optimization results. Reduction in fuel consumption by 1% at cruise conditions is achieved by adaptive morphing of the trailing edge for the typical long-range two-aisle air vehicle. The morphing of the trailing edge has a high level of technological availability and can be implemented in existing aeroplanes to reduce drag as far as possible for each flight condition.

Besides in the work [Ninian, D.; Dakka, S.M., 2017] the wings for morphing were designed – innovative technology, which has potential to improve aerodynamic efficiency (feature) and reduction in aircraft noise patterns. This research was focused on the reduction of induced drag caused by lifting force on the flaps of the airfoil section and improvement of the design to reach aerodynamic efficiency (Table 4.21). Modelling has shown almost 11% growth of the lift factor for the initial morphing wing and 15,4% for the optimized morphing wing compared to the traditional wing layout. At angles of attack 0, 5, 10 and 15 degrees the optimized wing has the gain in aerodynamic efficiency by 18,3 %, 10,5 %, 10,6 % and 4 % respectively compared to the common wing. Modelling also showed that there is considerable improvement of pressure distribution at a lower surface of the wing with morphing. An increase in the flow smoothness and decrease in vortex dimension along the wing trailing edge led to drag reduction. It was observed also pressure rise on the lower

surface. The morphing ring reduced the vortex dimension; therefore, the noise levels measured were reduced by 50%.

Angle of attack, deg.	Noise level of traditional wing, dB	Noise level of adaptive wing, dB	Noise level of air tunnel, dB
0	68	63	62
5	68	65	
10	69	67	
15	70	67	
20	71	69	

Table 4.21: Noise level of traditional and adaptive (morphing) wings in the air tunnel

All aircraft emit CO_2 is a fuel combustion product. Fuel use by the global aircraft fleet has increased approximately linearly over four decades (up to 2013) based on International Energy Agency estimates. Fuel use per revenue passenger kilometre (RPK) has decreased since the 1970s as aircraft structures, aircraft engines and aircraft operations have become more fuel-efficient [Lee *et al.*, 2009]. Aviation fuel use and CO_2 emissions are projected to continue increasing in the coming decades as aviation demand increases, even as CO_2 per RPK decreases due to technological and operational improvements.

Therefore, improving fuel efficiency is a key method of reducing CO_2 emissions. Fuel represents approximately 20% of the total operating costs for modern aircraft [Kahn Ribeiro, et al., 2007]. It is expected that market forces lead airlines to minimize fuel consumption, for example, through the introduction of new technologies in aviation [Holland, M., 2011]. Since 1960, fuel efficiency has improved by about 70-80%. Some assessments indicate that by 2050 another 40-50% improvement can be achieved [Kahn Ribeiro, et al., 2007]. The main areas for improving the overall fuel efficiency of an aircraft are:

1. Aircraft weight reduction.

2. Improvement on the aerodynamics of aircraft to reduce aerodynamic drag.

3. Improvement of the specific efficiency of the engine to reduce fuel consumption per thrust unit [King, D., et al., 2010].

The weight reduction of aircraft was achieved through the introduction of light advanced alloys and composite materials, new designs for aviation systems, improved and new production processes. For example, the Boeing 787 entered service in 2011 and has an airframe made up of almost 50% carbon fiber reinforced plastic and other composites, offering an average weight reduction of 20% compared to similar traditional aluminium structures. Just as an example of the introduction of new technologies aimed at reducing fuel consumption and reducing emissions of pollutants, the scheme of the Airbus A350XWBis presented (Figure 4.88). The future volume of aircraft emissions will be determined by the intensity of air traffic, air traffic control, new aviation technologies and the speed of change in the fleet of aircraft.

During the combustion of hydrocarbon-based fuels, aircraft engines generate gaseous and particulate matter (PM) emissions. At the engine exhaust, particulate emissions consist mainly of ultrafine soot or black carbon emissions. These particles, referred to as "non-volatile" PM (nvPM), are present at high temperatures, in the engine exhaust. Compared to conventional diesel engines, gas turbine engines emit non-volatile particles of smaller mean diameter. Their characteristic size ranges roughly from 15 to 60 nanometres (nm; 1nm = 1/100,000 of a millimetre). These particles are invisible to the human eye and are ultrafine. The CAEP/11 meeting recommended new nvPM mass and number Standard for aircraft engines and this will be considered by the ICAO Council for adoption in the early part of 2020. The new Standard will apply to new type and in-production engines with rated thrust greater than 26.7kN from 1 January 2023. The limit lines for nvPM mass

and number provide some alleviation for engines with rated thrusts below 150kN. This Standard is less stringent for in-production engines and a supplementary "no-backsliding" measure was introduced.

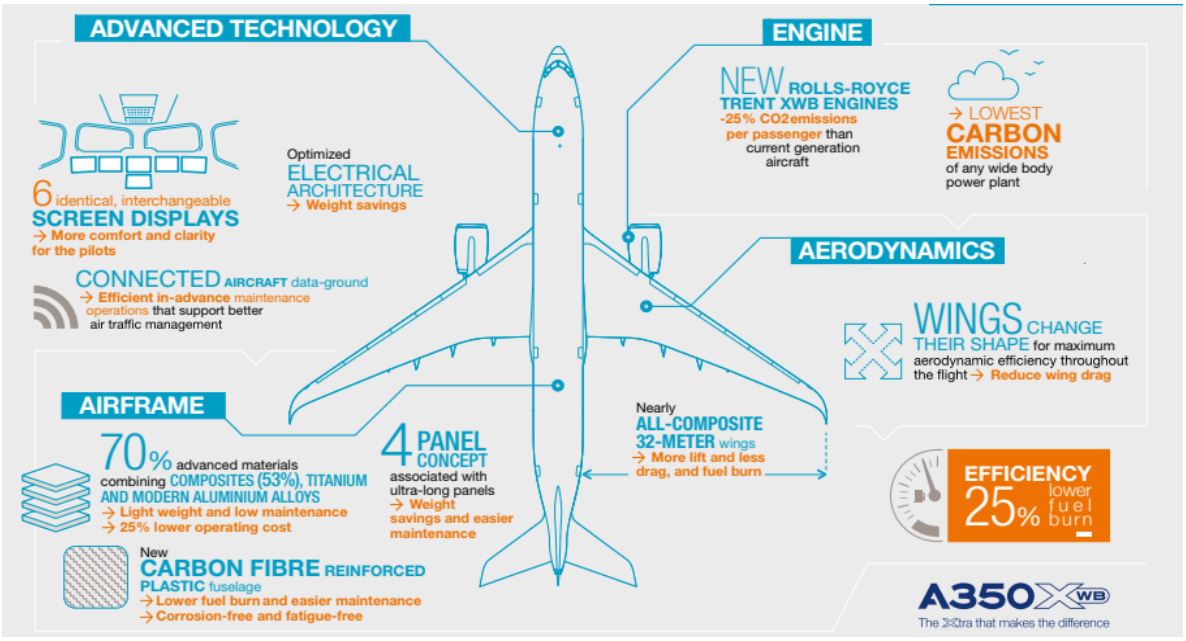


Figure 4.88: Advanced Airbus Technologies

The recommendation on the nvPM emissions Standard was supported by a significant data-driven process and the cost-effectiveness modelling analysis of several different stringency options for mass and number. In addition, CAEP agreed on an end date for the Smoke Number Standard, of 1 January 2023, as the new nvPM emissions Standards preserve ICAO smoke visibility limit. With this new Standard, ICAO will have completed the main environmental Standards for the certification of aircraft and engines, namely for noise, local air quality (NOx, HC, CO, nvPM) and climate change (CO_2), making the aviation industry the only sector with mandatory environmental certification requirements at the global level for the operation of its equipment. Once applicable, all new aircraft will need to be certified to these ICAO Standards before operating.

The new nvPM standard is the first of its kind, and it includes a full standardized certification procedure for the measurement of nvPM, and the regulatory limit for the nvPM mass concentration set at the current ICAO smoke visibility limit. The new nvPM standard is recommended as a new Chapter to Annex 16, Volume II. The agreement on the new nvPM standard will set the basis for a more stringent nvPM standard during CAEP/11.

A consensus appears that nvPM reduction must be also achieved, in addition to NOx. This induces critical R&T on [FORUM-AE, 2015]:

- The combustor technology itself to ensure both NOx & nvPM ambitious low levels: enhanced lean combustion in general (achieving TRL6 maturity & extending its application to a smaller size and/or smaller OPR engine combustors), and focus on more specific aspects which may be beneficial to particles reduction (improved atomisation);
- The modelling of emissions, which for particles emissions is far from being predictable today, because of the physical complexity of particles formation (gaseous precursors formation, particles nucleation & oxidation…), and the modelling of combustion-related operability aspects;
- The experimental analysis, which is necessary to support modelling development or to assess technology. This assumes advanced measurements (in particular intrusive and non-intrusive

measurements of particles in the combustion chamber) and appropriate test capability (from multi-sector tests to full annular tests, with ability to achieve high-pressure levels).

CAEP will also continue to monitor and review technology developments, including combustion technologies and advances in engine combustor design, with a view to understanding how these technologies may impact the production of gaseous emissions and PM in the future. The recommendation on the new nvPM mass and number Standard was accompanied by an agreement by CAEP to conduct an early review of the relevant regulatory levels. This will involve the collation and analysis of the certified and certification-like nvPM mass and number emissions data that will become available for all in-production engines during the period 2019 to 2022. The margins to the agreed CAEP/11 nvPM SARPs will be reviewed to assess possible technological advancements to reduce nvPM emissions.

During the current CAEP/12 cycle it is also planned to conduct a scoping study for NOx for in-production engines to investigate the feasibility for further NOx stringency analysis. ICAO continues to monitor developments in aeroplane and engine applications, and concepts to develop methodologies for emissions certification. In addition, advancements in supersonic technologies are being monitored to assess possible consequences for aeroplane and engine based emissions and an exploratory study to provide a better understanding of airport noise impacts resulting from the introduction of supersonic aircraft is ongoing.

The impact of aviation on the environment has increased as a result of increased air traffic. Between 1990 and 2005, the number of aviation and CO_2 emissions increased by about 80%. However, due to technological improvements, fleet renewal, the increased efficiency of air traffic control and the economic downturn in 2008, the level of emissions and noise in 2014 was approximately at the level of 2005.

The experimental demonstrator Airbus A340 with a laminar flow «BLADE» (A340-300 MSN001) made the successful maiden flight under BLADE project funded by EC. The aircraft is equipped with two outer transonic wing boxes. Several hundreds of points to measure surface undulation are fitted on the wing in order to study out the influence of undulation on the laminar boundary layer. There are employed infrared cameras to measure wing temperature along with an acoustic generator, which measures the effect of acoustics on the laminar flow. Moreover, there is an advanced reflectometry system, which measures general deformation in real-time in flight.

The main aim of BLADE project is to measure admissible deviations and drawbacks of the surface, at which the laminar flow is supported. To this end, Airbus will simulate all imperfection types, and as a result, the tolerances to create the laminar wing will be known completely. BLADE project is organized in the frame of the aeronautical research programme "Clean Sky" in Europe. 21 European partners take part in Blade project with 500 participants including GKN Aerospace – designer of an onboard panel with laminar flow and SAAB is designer of the wing segment.

The Airbus company presented updated aircraft A380, named A380plus in 2017 with extended range, greater passenger capacity and reduced fuel consumption. New winglet airfoils together with other wing upgrading improve aerodynamics and reduce drag that leads to 4% fuel economy. In doing so the aircraft meets the dimension requirements - 80x80 meters for compatibility of the aircraft with airport infrastructure [*http://www.airbus.com/aircraft/passenger-aircraft/a380-family.html*].

Speaking about the level of aircraft aerodynamic excellence, which determines its competitiveness nowadays, it makes sense to address to the definite example - long-range civil aircraft B-787 [Goldhammer M., 2011]. The maximum effect on the improvement of its common efficiency was reached due to the employment of new engines. Owing to the mastering of the systems including avionics and accessories it was managed to improve quality approximately by 15%. New materials considerably contributed as long as composites in B-787 made 50% of the aircraft weight. Mastering of aerodynamics made possible to improve the efficiency of the new aircraft approximately by 20%.

Aeroplanes of the type "flying wing" are the other conceptual directions. One of them is HWB concept (hybrid wing-body). NASA and Lockheed Martin studied fuel consumption of the HWB concept. They concluded that positioning of engines over the trailing edge of a wing reduces drag on flats. In general, HWB aircraft have better aerodynamic properties than those with a traditional configuration that in turn leads to a considerable reduction of fuel consumption and emissions [Warwick G., 2017].

As for NASA estimation, the optimum HWB configuration will consume maximum 114 tons of fuel per one flight compared to Boeing 777, which consumes 142 tons of fuel per flight [Burley C.L., Olson E.D., Thomas R.H., 2017]. National Oceanic and Atmospheric Administration claim that at average 28537 commercial flights are accounted for daily in the United States. If every commercial aircraft is of HWB type, then it would make 799036 tons per day of total fuel reduction. Annually it will make approximately 292 million tons of fuel consumption saving only for commercial flights in the USA. Such fuel saving would make HWB aircraft more ecological and economical than modern aeroplanes, that would be advantageous especially taking into account the growing problem of greenhouse gases effect.

One more ecological problem, which HWB aircraft can help to solve, is noise pollution effect on animals. Cambridge philosophic society has gathered the data of two decades of researches on the effect of human noise on wildlife. The conclusion was made that any noise higher than 40 dB effects on animals. The high noise level is "harmful for wildlife and natural ecosystems". In particular transport noise sources including commercial aeroplanes can affect on vocal behaviour, motion, physiology and population species indices.

Earlier researchers hoped that HWB design would have been used by the year 2020, but still there are obstacles to be overcome [Burley C.L., Olson E.D., Thomas R.H., 2017]. The bigger part of the technology under study is still at s concept stage and the landing gear introduces more noise than wanted. For HWB aeroplanes, which will be commercial ones in future, further research is required. However, having surpassed those limitations, the HWB aircraft can make a positive effect on the environment due to reduction of noise pollution, fuel consumption and aircraft emission. This is also a step to improve the life of people, who encounter large volumes of the aircraft intrusive noise. In the course of HWB technology development, it offers hope not only for life and environment improvement but for the revolution in the field of commercial aviation.

The main limitation of HWB aeroplanes is a large volume of noise generated by their landing gear at land approach. Compared to the traditional design layout scheme of aeroplanes and wings the landing gear of HWB design makes much more noise. It is due to airframe geometry around the landing gear location. On the flat with a tube, the landing gear is placed under the wing part nearest to a fuselage. This area has a low-speed airflow; therefore, the landing gear does not cause a lot of noise [Guo Y., Thomas R. H., 2015]. As for the HWB design the landing gear is located in the same common area, but the local geometry of the airframe in this area is different. As long as the body and the wing is one uninterrupted part the airflow accelerates in this area. Therefore, the landing gear becomes an obstacle for movement of high-speed air. The landing gear noise is proportional to airflow speed, so it makes more noise. 20% increase in airflow speed around the landing gear leads to increase in HWB noise level by 6 dB [Guo Y., Thomas R. H., 2015]. It's a counter effect from the HWB design. Researchers hope to use HWB design for a reduction but not for an increase in EPNL aggregate amount; therefore, it is needed to find the solution of the landing gear noise problem. However, HWB design has several existing limitations. Still, there is a big hope that it can be employed for the reduction of noise pollution and have a positive effect on the environment.

The eighth meeting of ICAO's Committee on Aviation Environmental Protection (CAEP/8) held in February 2010, made important decisions regarding technological means to reduce the impact of aviation on climate change. It was agreed that the effort would be referred to as a "CO_2 Standard" based on "fuel efficiency concepts" within the certification requirement metric. This was decided to ensure the necessary transparency and public understanding that is essential to demonstrate that this work is contributing to efforts to reduce aviation's impact on climate change.

Following six years of development, ICAO's CAEP at its tenth meeting (CAEP/10) recommended an Aeroplane Carbon Dioxide (CO_2) Emissions Certification Standard. This new standard is a part of the ICAO "basket of measures" to reduce greenhouse gas emissions from the air transport system, and it is the first global technology Standard for CO_2 emissions for any sector with to encourage more fuel-efficient technologies into aeroplane designs.

The recommended CO_2 Standard has been developed at the aeroplane level and therefore has considered all technologies associated with the aeroplane design (e.g. propulsion, aerodynamics and structures). Once adopted by the ICAO Council, the Aeroplane CO_2 Emissions Certification Standard will be published as a new Annex 16, Volume III. The framework for the CO_2 Standard consists of a certification requirement and regulatory limit, as shown in Figure 4.89, and the work to develop the CO_2 Standard was divided into two phases. Phase 1, which was completed at the ninth meeting of the CAEP (CAEP/9) in February 2013, resulted in the approval of some of the details regarding the applicability of the Standard, the CO_2 Metric System and the development of a CO_2 Standard certification requirement. Phase 2 involved the development of the regulatory limit lines and the applicability requirements such as scope and date.

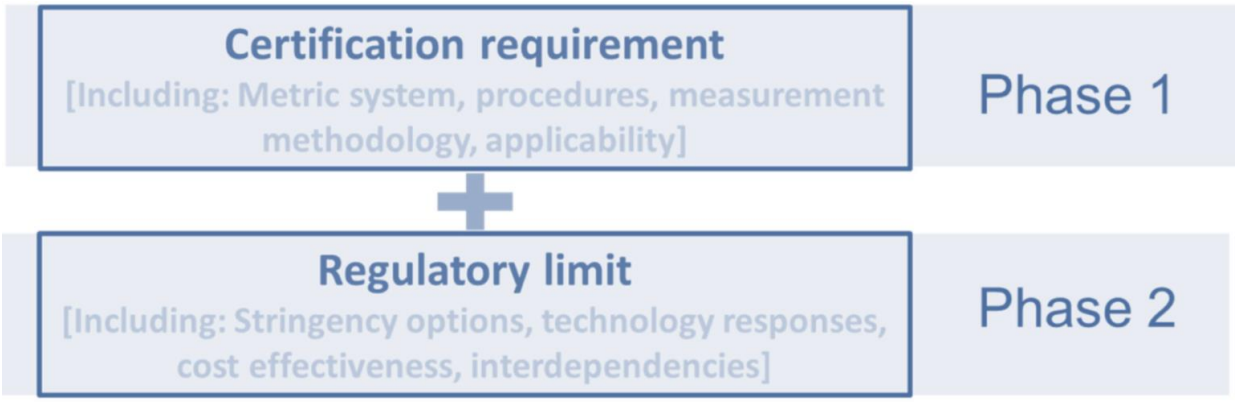


Figure 4.89: The framework and development phases of the CO_2 Standard

The results of the CAEP/10 meeting were unprecedented because it was the first time CAEP had been able to recommend two completely new standards in one meeting, on CO_2 and non-volatile particulate matter (nvPM) emissions. The recommended Aeroplane CO_2 Emissions Certification Standard is a technology standard to encourage more fuel-efficient technologies into aeroplane designs. This technology-based approach is similar to the current ICAO engine emissions standards for LAQ and the aircraft noise standards. The recommended CO_2 standard has been developed at the aeroplane level and therefore has considered all technologies associated with the aeroplane design (e.g. propulsion, aerodynamics and structures). This approach is similar to the current ICAO aircraft noise standards. The CO_2 standard will apply to subsonic jet and turboprop aeroplanes that are new type (NT) designs from 2020, as well as to those aeroplane type designs that are in-production (InP) in 2023 and change. Regarding the latter, if after 2023 any InP aeroplane type design that is changed to the extent that it triggers applicability, it would then need to be made compliant with the standard. In 2028, there is a production cut-off. This means that InP aeroplanes that do not meet the standard can no longer be produced from 2028 unless the designs are modified to comply with the standard.

The recommendation on the CO_2 emissions standard was supported by a significant data-driven process and the cost-benefit modelling analysis of several different CO_2 stringency options. The new CO_2 emissions Standard is recommended as being included in an entirely new Volume to Annex 16 (Volume III). Figure 4.90 shows an overview of the CO_2 Standard regulatory limit lines for both NT and InP CO_2 Standards.

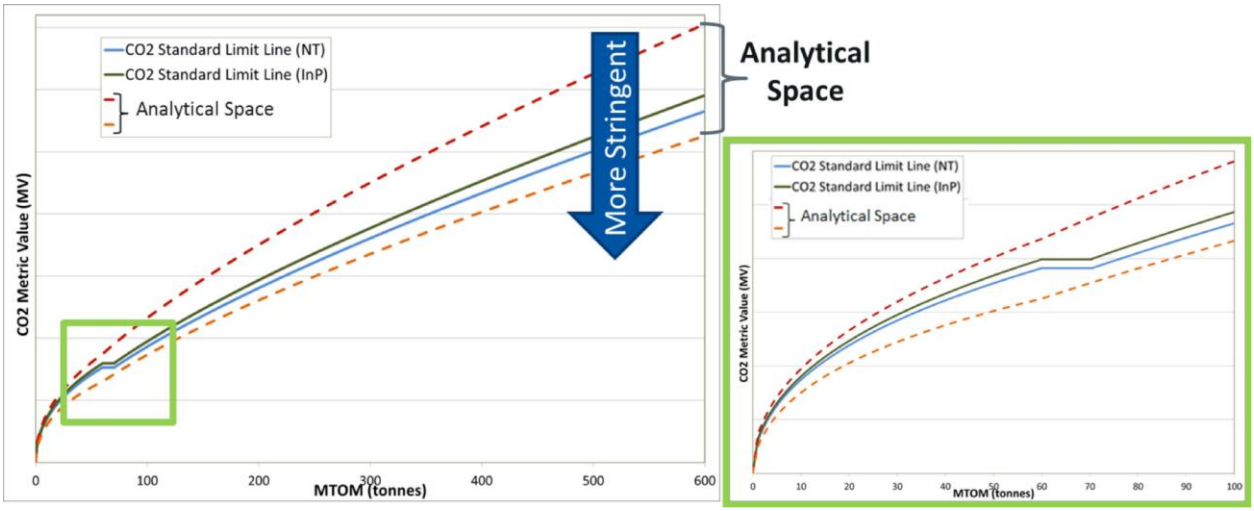


Figure 4.90: The CO_2 Standard regulatory limits for the aircraft

The CO_2 Standard covers a broad range of aeroplane masses and types and is especially stringent where it will have the greatest impact: for larger aeroplane types with an MTOM of greater than 60 tonnes. CAEP considers technical feasibility very carefully during the development of environmental standards, and as such, the decision at CAEP10 recognised the fact that the larger aeroplane designs have access to the broadest range of CO_2 emissions reduction technologies. This is less so for aeroplanes below 60 tonnes where the standard provides an additional margin for a sector. This is particularly recognised for aeroplanes of MTOMs less than 60 tonnes and with fewer than 19 seats maximum passenger seating capacity, where for new aeroplane type designs the applicability date of the standard is 2023.

It is complex to fully understand the impact of the CO_2 Standard due to potential unknown market-driven responses to the regulation, and the fact that the CO_2 Standard cost-effectiveness analysis was a comparative investigation of regulatory limit lines. However, the new standard will have direct effects by increasing the importance of fuel efficiency in the design process such that an aeroplane type not just meets the regulatory limit but also has good relative product positioning in terms of a margin to the limit.

4.1.5. Cruise efficiency and global emissions

ICAO and its Member States have recognized the impact of the emissions from international aviation on the global climate, and have resolved to minimize this impact while ensuring the sustainable growth of international aviation. Air transport accounts for 2% of global man-made CO_2 emissions. In 2017, civil aviation, as a whole, emitted around 859 million tonnes of CO_2, which is roughly 2% of man-made carbon emissions (Figure 4.2).

In 2010, Member States agreed to work through the ICAO to achieve a global annual average fuel efficiency improvement of 2% and to stabilize the global net carbon emissions of international aviation at 2020 levels. During 2012, Member States submitted voluntary Action Plans to the ICAO outlining their annual reporting on international aviation CO_2 emissions and their respective policies and actions to limit or reduce the impact of aviation on the global climate. New or updated action plans were submitted during 2015 and are expected once every three years thereafter.

In 2012, aviation represented 13% of all EU transport CO_2 emissions and 3% of the total EU CO_2 emissions. It was also estimated that European aviation represented 22% of global aviation's CO_2 emissions. Similarly, aviation now comprises 14% of all EU transport NOx emissions and 7% of the total EU NO_x emissions. In absolute terms, NO_x emissions from aviation have doubled since 1990, and their relative share has quadrupled, as other economic sectors have achieved significant reductions [EEA, Transport and Environment Reporting Mechanism 2014].

Amongst the four pillars (technology, operations, infrastructure, economic measures) of aviation's strategy to reduce CO_2 emissions in half by 2050 (relative to 2005 levels), ***technology*** and ***sustainable aviation fuels*** (SAF) collectively deliver the highest improvement benefits. Continuous technological improvement of aircraft fuel efficiency plays a crucial role in working towards the 2050 carbon reduction goal. In fact, since the beginning of the jet age, technological innovations such as lighter materials, higher engine performance and aerodynamic improvements have reduced fuel consumption per passenger-km or ton-km of aircraft by over 70%. Further substantial reductions from new technologies are expected in future [**Aircraft Technology Roadmap to 2050, 2018**].

Combining air traffic and environmental indicators together show some signs of growing economic and connectivity benefits from aviation (measured in passenger-kilometres flown) without a proportionate increase in environmental impact (Figure 4.12). The diverging trends of passenger-kilometres flown and noise energy between 2005 and 2014 have shown that this is possible and that there is the potential for this to continue in the future. Nevertheless, the absolute noise energy and emissions of aviation are expected to grow further in the next twenty years.

Aircraft emit gases and aerosol that change the composition of the atmosphere, because increases in cloudiness through contrail formation and spreading, and modify natural clouds. At present, these changes together are estimated to cause a net positive forcing of Earth's climate system, which contributes to surface warming and other responses. There is a substantial understanding of the components of aviation climate forcing, particularly CO_2. Important uncertainties remain in quantifying some of the aviation non-CO_2 climate terms and in the underlying physical processes. This paper presents a summary of recent progress in the state of the science since the 2012 ICAO/CAEP/ISG paper, especially related to contrails and induced cloudiness, contrail avoidance, and aerosol and NO_x effects. The number and diversity of newly available studies have created a need to re-evaluate best estimates of aviation climate forcing. Our understanding and confidence in aviation climate forcing's would be enhanced by a new international scientific assessment.

'Radiative Forcing' (RF, in watts per square metre) is used to quantify present-day impacts from current and (largely) historical emissions (in the case of long-lived greenhouse gases) as it has an approximately linear relationship with the equilibrium global mean surface temperature change (ΔT_s in Kelvin) since the onset of industrialization:

$$\Delta T_s = \lambda RF$$

where λ is the climate sensitivity parameter in $K(Wm^{-2})^{-1}$. For various impact factors the RF is shown in Figure 4.91. Since IPCC AR5 [AR5 Synthesis Report, 2014], the scientific community is now using the 'Effective Radiative Forcing' (ERF), since it accounts for fast feedbacks from e.g. clouds, aerosols better and has a better relationship with ΔT_s.

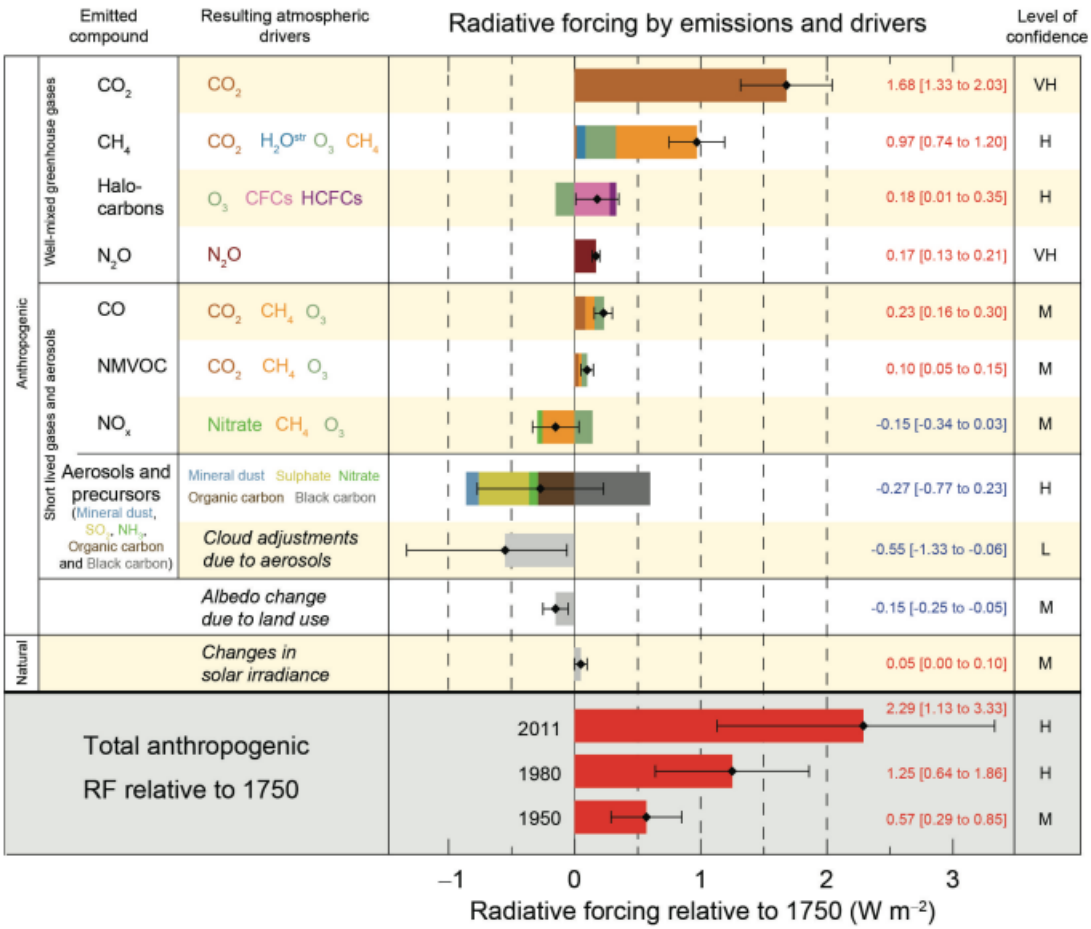


Figure 4.91: Radiative forcing by emissions and drivers [AR5 Synthesis Report, 2014]

The connections between aviation emissions and radiative forcing, climate change, and its impacts and potential damages are shown in Figure 4.92. The principal greenhouse gases (GHGs) emitted are carbon dioxide (CO_2) and water vapour (H_2O). Emissions of nitrogen oxides (NOx) impact the concentrations of other GHGs, mainly ozone (O_3) and methane (CH_4). Black carbon (soot) is a directly emitted aerosol, and sulphur oxides (SO_x), NO_x, and hydrocarbons (HC) lead to aerosol production after emission. Water vapour emissions in combination with emitted or background aerosol lead to contrail formation. Persistent contrails, which form at high ambient humidity and low temperatures, increasing cloudiness. Additionally, aviation aerosol may modify natural clouds or trigger cloud formation. There is high confidence that these are the primary pathways by which aviation operations affect climate.

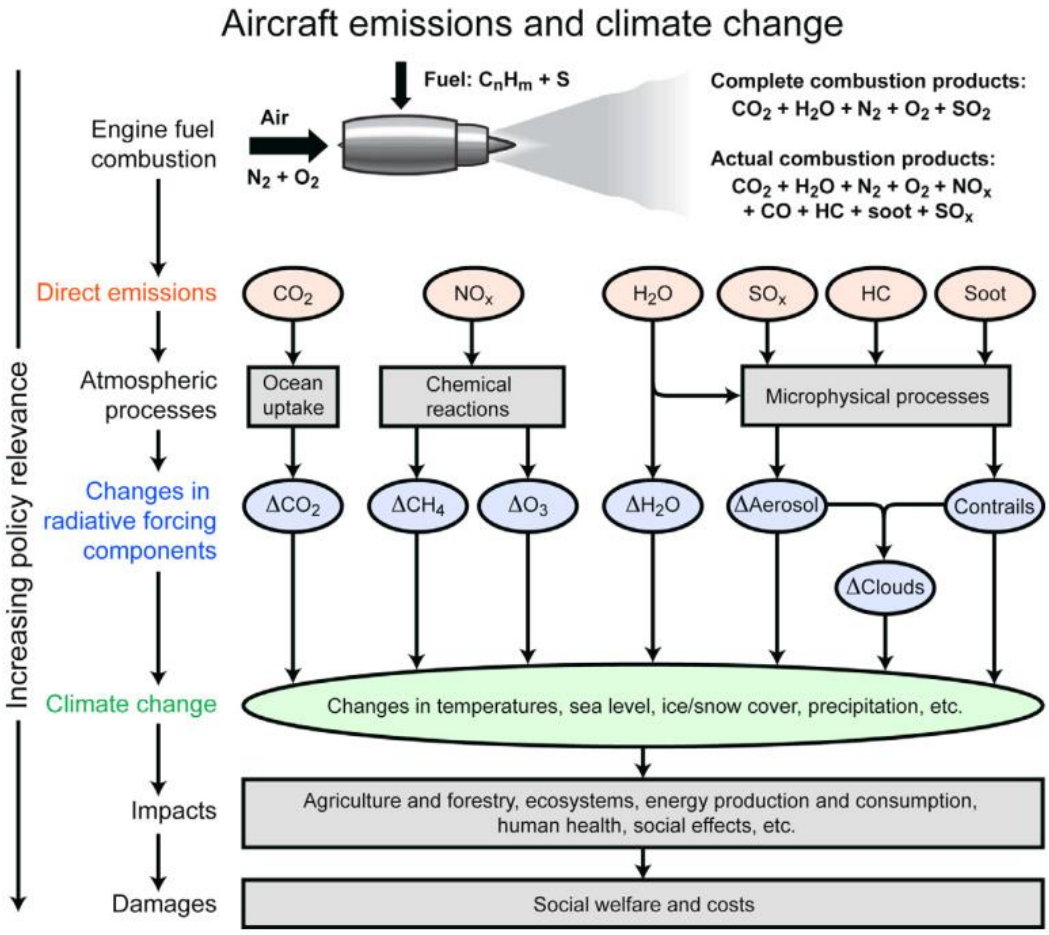


Figure 4.92: Updated schematic of the principal emissions from aviation operations and the relationship of emissions to climate change and impacts. The terminology, ΔX, indicates a change in component X. The term ΔClouds represents contrail induced cloudiness and aerosol-cloud interactions [Brasseur et al., 2015]

The evaluation requires knowledge of many physical and chemical processes in the atmosphere and requires summing over the global aircraft fleet operating under diverse meteorological conditions in the upper troposphere and lower stratosphere where most emissions occur. The [Lee *et al.,* 2009] study is the most recent assessment in the literature of the best estimates of aviation RF terms.

The annual contribution of global aviation to the total radiative forcing associated with anthropogenic activities is considered to be about 3.5%, increasing to about 4.9% when the effects of aircraft-induced cloudiness (AIC) are included [Lee *et al.,* 2009]. The envisaged increase in air traffic, however, is a major concern when viewed together with the current rate of technological improvement.

The recent ACCRI report drew similar conclusions in noting that recommendations for best estimates were precluded in their study due in part to the varied modelling approaches that did not all account for climate system couplings and feedback processes [Brasseur *et al.,* 2015]. Continued progress in understanding and quantifying aviation climate forcing and responses requires continued focused research activities and would be enhanced by a new international scientific assessment that would assess newly published results available, for example, for contrails, contrail cirrus and indirect cloud effects. An updated science assessment would also identify important remaining gaps in understanding and, hence, guide future research directions.

Paragraph 9 in [ICAO Resolution A40-18, 2019]: "The Assembly… Requests the Council to continue to explore the feasibility of a long-term global aspirational goal for international aviation, through conducting detailed

studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented to the 41st Session of the ICAO Assembly. Assessment of long-term goals should include information from Member States on their experiences working towards the medium-term goal". Paris Agreement on this subject continue for more intensive emission reduction strategies: "… emission pathways consistent with holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C".

CO_2 emissions have risen steadily over the last decades & show no sign of peaking, Figure 4.93. The 2019 projection is based on preliminary data and modelling [Friedlingstein et al, 2019], fossil CO_2 emissions will likely be 62% higher in 2019 than the year of the 1st IPCC report in 1990. This rate of the CO_2 emission could exceed the 1.5°C rise in few decades, Figure 4.94. Limiting global warming to 1.5°C would avoid catastrophic impacts:

- We are already seeing some dangerous impacts at 1°C;
- 1.5°C would cause accelerating global climate damages.

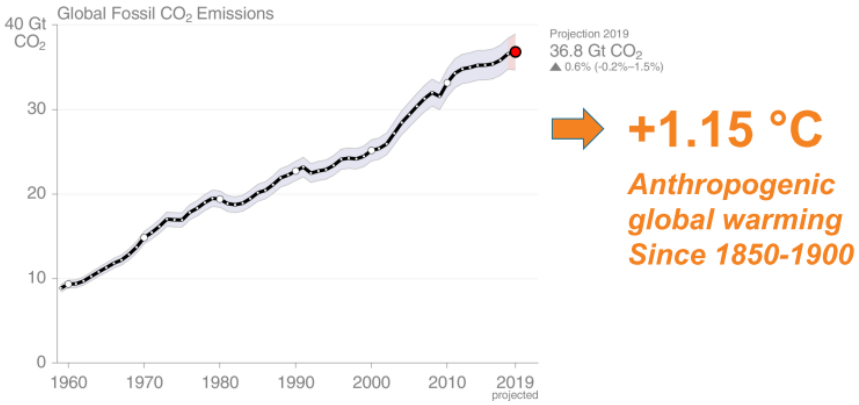


Figure 4.93: Global CO_2 emissions are still increasing (Global carbon project, 2019 update)

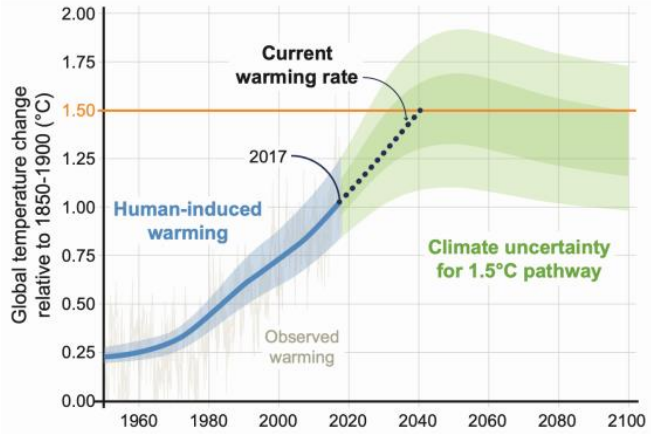


Figure 4.94: Global temperature change may exceed 1.5°C in few decades

Meeting the goals of the Paris Agreement will require rapid near-term emissions reductions [Matthews D., Lee D.S. Fahey D., Fuglestvedt J.S., 2020]:

- 1.5°C scenarios: net-zero CO_2 emissions before 2050 + substantial reductions of other greenhouse gas emissions
- "Well below 2°C" scenarios: net zero CO_2 emission after 2050 + reductions of other greenhouse

gas emissions

- Total CO_2 emissions determine future warming
- Slower reductions now will require faster reductions later, and likely more extreme negative emissions.

Aircraft CO_2 emissions increased from 88 to 156 million tonnes (+77%) between 1990 and 2005 according to the data reported by EU28 and the EFTA Members States to the United Nations Framework Convention on Climate Change (UNFCCC) (Figure 4.13). According to these data from the EU IMPACT emissions model, CO_2 emissions increased by 5% between 2005 and 2019, which is however less than the increase in passenger-kilometres flown over the same period. This was due to an improvement in fuel-efficiency driven by the introduction of new aircraft, removal of older aircraft, and improvements in operational practice. The average fuel burn per passenger kilometre flown for passenger aircraft, excluding business aviation, went down by 19% over this same period. However, projections indicate that future technology improvements are unlikely to balance the effect of future traffic growth. Under the base traffic forecast and advanced technology improvement rate, CO_2 emissions increases by 44% from 144 Mt in 2005 to 207 Mt in 2035.

Current and future technological developments to achieve the challenging ACARE 2050 CO_2 goal are essential to mitigate substantially the increase of aviation CO_2, with realistic traffic growth assumption (Figure 4.95). A large part of the effort of the last decade was supported within Clean Sky, and within other European projects like LEMCOTEC, ENOVAL and E-BREAK.

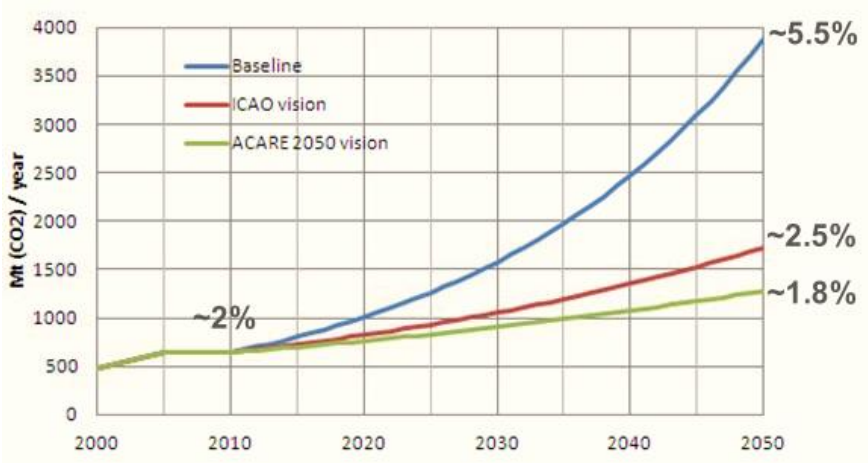


Figure 4.95: Global aviation CO_2 forecast with ACARE assumption
(Assumptions: ACARE 2050 is achieved in 2050 and fully introduced in the 2050 fleet; there is a continuous improvement of average effiency from now to 2050; ICAO 37th assembly average traffic growth of 4.6% is taken)

Most promising solutions appear to be laminar wing, and ultra-high by-pass ratio engines like Open Rotor (medium-term) and distributed propulsion (longer-term as explored in DISPURSAL project). New and light materials (e.g. composites for fan blade) should also provide benefits. It is unclear what is projected on new aircraft architectures before 2050, but AHEAD project illustrates a radical aircraft configuration change.

A new assessment was performed against ACARE CO_2 and NO_x goals and is summarized in the following Table 4.22. Although there is no ACARE objective related to ultrafine particles, this is now a key environmental and regulatory concern, which requires appropriate mitigation solutions (combustor technology and fuel composition).

	Reference 2000	ACARE 2020 Goals (at TRL6)		ACARE 2050 Goals (at TRL6)	
		High Level	detailed (SRA)	High Level	detailed (SRIA)
CO2	*Representative technology of aircraft & engine with 2000 EIS, & representative 2000 ATM*	"-50% per pass km"	aircraft: -20% to -25% engine: -15% to -20% ATM: -5% to -10%	"-75% per pass km"	aircraft & engine: -68% ATM: -12% Other: -12%
NOx (LTO)		"-80%"	engine: -60% CAEP6 ; complement achieved by aircraft + ATM	"-90%"	engine: -75% CAEP6 ; complement achieved by aircraft + ATM
NOx (Cruise)		"-80%"	Achieved through -50% Fuel Burn & -60% cruise EINOx reduction	"-90%"	Achieved through -75% Fuel Burn & further cruise EINOx reduction
Other emissions		"damaging emissions reduced"	emissions qualitatively reduced (particles, CO, UHC) and better understanding of impacts	"emissions-free taxiing" + qualitative reduction	knowlegde of emissions (particles, VOC) and better understanding of impacts

Table 4.22: FORUM-AE assessment against ACARE emissions goals [FORUM-AE, 2015]

Figure 4.96 presents full-flight CO_2 emissions for international aviation from 2005 to 2040, and then extrapolated to 2050. It only considers the CO_2 emissions associated with the combustion of jet fuel, assuming that 1 kg of jet fuel burned generates 3.16 kg of CO_2, similar to Figure 4.3. As with the fuel burn analysis, this analysis considers the contribution of aircraft technology, improved air traffic management and infrastructure use (i.e., operational improvements). In addition, the range of possible CO_2 emissions in 2020 is displayed for reference to the global aspirational goal of keeping the net CO_2 emissions at this level. Based on the maximum anticipated fuel consumption in 2020 and the anticipated scenario of fuel consumption in 2040, a minimum CO_2 emission gap of 523 Mt is projected in 2040. Extrapolating this scenario to 2050 results in a 1,039 Mt gap [ICAO Environmental Report 2016].

Figure 4.97 provides results for global full-flight fuel burn for international aviation from 2005 to 2040, and then extrapolated to 2050 with the contribution of aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements) to reduce fuel consumption. The Figure 4.97 is an analogue of more recent calculations shown for this trend in Figure 4.2 and it also illustrates the fuel burn that would be expected if ICAO's 2% annual fuel efficiency aspirational goal were achieved. The trends presented in Figures 4.96 and 4.97 were developed in the context of a longer-term view. Short term changes in global fuel efficiency can be affected substantially by a wide range of factors such as fluctuations in fuel prices, and global economic conditions.

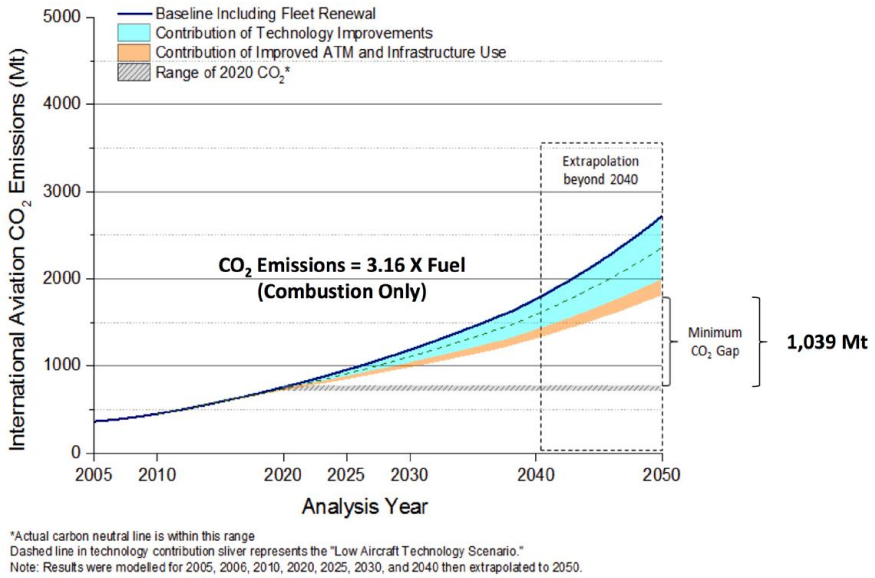


Figure 4.96: CO_2 Emissions Trends from International Aviation, 2005 to 2050 [ICAO Environmental Report 2016]

Due to improvements in aircraft design (more composite materials in aircraft construction – less weight), higher aerodynamic efficiency and improvements on engine fuel consumption per thrust unit the 2020 goal in fuel efficiency and consequently – in CO_2 emission reduction has been reached for all aircraft groups, what is shown in Table 4.23 for character aircraft tuypes of these groups.In the narrow-body segment, the extent to which the Airbus A320neo family and the Boeing 737MAX will improve upon the fuel efficiency of their respective predecessors is now significantly greater than was understood in 2012.In the wide-body segment, four new aircraft types have been launched: the Airbus A330neo, Airbus-350 XWB, Boeing 777X and Boeing 787-10. Their fuel efficiency is higher than expected – 20-25%, especially the efficiency of Airbus-350 XWB is so dominant that Airbus-380 is not concurrent with it and a decision to stop its manufacturing was reached by Airbus Group SE.

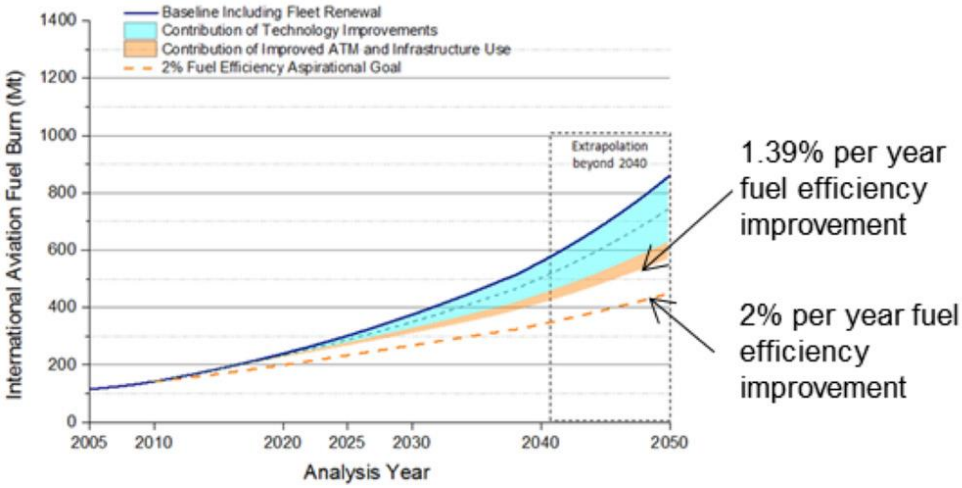


Figure 4.97: Fuel Burn Trends from International Aviation, 2005 to 2050 [ICAO Environmental Report 2016]

As such the fuel-efficiency characteristics of theseaircraft are well-defined and lead us to have a high degree of confidence in their impact, over time,upon fleet efficiency.**The ACARE 2020 Goal for aircraft fuel efficiency is looking reached first of all in Technology/Operation domain**, consequently the Goal for CO_2 reduction also

(Table 4.24). Overall fleet efficiency improvement associated with replacing baseline fleet with "*imminent*" aircraft is 22.0%.

Aircraft	Entry into service[56]	Manufacturers' claimed fuel efficiency improvement vs previous generation aircraft[57]	
		2016 Road-Map	2012 Road-Map (for comparison)
Bombardier C Series	2016	20	20
Embraer E2	2018	16 – 24	N/A
Airbus A320neo family	2015	19 – 23	15
Boeing 737 MAX	2017	14 – 20	10 -12
Airbus A321LR	2019	30	N/A
Airbus A330neo	2017	14	N/A
Boeing 787 Dreamliner	2011	20 – 25	20
Airbus A350 XWB	2015	25	25
Boeing 777X	2019	20	N/A
Airbus A380[58]	2007	40	17

Table 4.23: Aircraft fuel-efficiency improvement till 2020 intermidiate goal

CO_2 reduction goals and contributions	2020 Vision	2020 SRIA	2035 SRIA	2050 SRIA
Overall	**-50%**	**-43%**	**-60%**	**-75%**
Airframe energy need (efficiency)	-25%	-20%	-30%	-68%
Propulsion & power energy need (efficiency)	-20%	-20%	-30%	
ATM and infrastructure	-12%	-7%	-12%	-12%
NON infrastructure-related airlines operation	-4%	-4%	-7%	-12%

Table 4.24: Stepwise goal for aircraft CO_2 reduction between 2020-2050

Potential reductions in CO_2 emissions due toanticipated improvements in ATM efficiency and operational practices -assumed aircraft CO_2emission saving in three main categories (from UK aviation [Sustainable Aviation Progress Report 2015-2017]): ATM on 6.3%, APU substitution on 0.3%, Aircraft Operations on 2.1%. Total CO_2emission reduction may be reached on 8-9%. Opportunities for fuel savingsandCO_2emission by aircraft due to ATM improvements for optimal flight profile(Figure 4.98) are shown in Table 4.25.

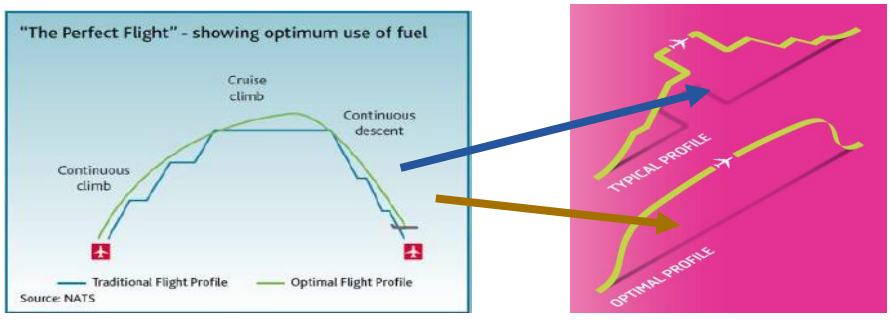


Figure 4.98: ATM improvements for fuel savingsby aircraftoptimal flight profile

Aircraft Type	Ground holding fuel burn (kg/min)	Taxiing fuel burn (kg/min)	Airborne holding fuel burn (kg/min) *	Continuous Descent fuel saving versus stepped descent with 10nm level off at 6,000ft (kgs) **	Continuous Climb fuel saving versus climb with 10nm level off at 6,000ft (kgs) ***	Cruise fuel burn at FL240 (kg/min) {Associated speed (kts)}	Cruise fuel burn at FL290 (kg/min) {Associated speed (kts)}	Cruise fuel burn at FL340 (kg/min) {Associated speed (kts)}	Cruise fuel burn at FL390 (kg/min) {Associated speed (kts)}
4 Engine Heavy	45	57	275	398	581	292 {478}	252 {497}	207 {487}	164 {482}
Small Heavy	19	23	148	215	300	137 {438}	119 {473}	99 {463}	79 {459}
Upper Medium	14	17	94	121	210	103 {412}	91 {445}	77 {463}	63 {459}
Medium	12	13	61	75	128	58 {412}	50 {445}	42 {452}	34 {447}
2 Engine Small Jet	7	9	38	48	77	34 {412}	29 {414}	24 {405}	19 {401}
Heavy Turboprop	4	5	17	2	29	19 {345}	-	-	-
Medium Turboprop	2	2	10	4	17	9 {242}	-	-	-

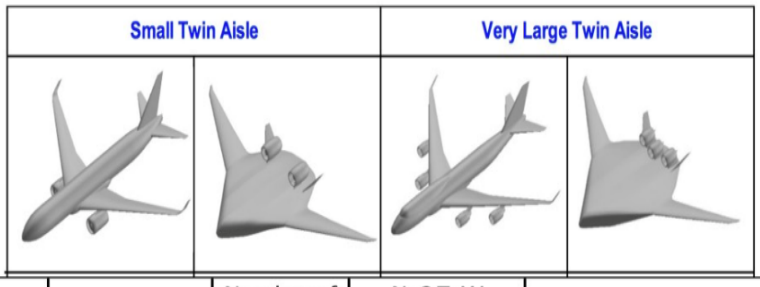
Assumptions

* Airborne holding: holding level at 8,000ft, with speed of 220kts
** Continuous Descent: Fuel saving with 10nm level off at 6,000ft compared to extra 10nm flown at cruise
*** Continuous Climb: Fuel saving with 10nm level off at 6,000ft compared to extra 10nm flown at cruise

Table 4.25: Opportunities for fuel savings by character aircraft groups

Future aircraft

The CO_2 emissions that affect the global climate and emissions that affect local air quality are expected to increase through 2050, but at a rate slower than aviation demand. Under an advanced aircraft technology and moderate operational improvement scenario, from 2030, aircraft noise exposure may no longer increase with an increase in traffic. However, it has to be kept in mind that the uncertainty associated with future aviation demand is notably larger than the range of contributions from technology and operational improvements.Figure 4.99 [Nickol, C., Haller, W., 2016] shows us existing and promising NASA aircraft to reach the goals.



Vehicle Class	Abbreviation	Number of Passengers	N+2 T+W Nomenclature	Unconventional	Abbreviation
Regional Jet	RJ	98	T+W98	Over-Wing-Nacelle	OWN98
Single Aisle	SA	160	T+W160	Over-Wing-Nacelle	OWN160
Small Twin Aisle	STA	216	T+W216	Hybrid-Wing-Body	HWB216
Large Twin Aisle	LTA	301	T+W301	Hybrid-Wing-Body Mid-Fuselage Nacelle	HWB301 MFN301
Very Large Twin Aisle	VLTA	400	T+W400	Hybrid-Wing-Body	HWB400

Figure 4.99: NASA N+2 aircraft generation

NASA, in the framework of its Environmentally Responsible Aviation (ERA) program, has set goals for the development of new technologies for future aircraft generations ("N+1/N+2/N+3") regarding the reduction of fuel consumption, noise and NOx emissions. These refer to the availability of technologies at a relative early technology readiness level (TRL) of 4 to 6. The following goals are set by NASA ERA program for fuel or energy consumption reduction:

- N+2: by 2020, 50% relative to 777-200 (entry into service: 2030 – 2035)
- N+3: by 2025, 60% relative to 737-800 (entry into service: 2035 – 2040)

It is expected that the new designs of N+2 aircraft generation will significantly reduce fuel consumption compared to the best existing aircraft. In this analysis, it is assumed that the NASA N+2 generation aircraft can be accessed in 2030. So, in the work [Padalkar R., 2017] prediction was conducted for 4 different scenarios.

Scenario 1 is an alternative to "do nothing" without N+1 and N+2 aircraft types entered into the structure. The purpose of the baseline scenario is to understand the future in which the current aircraft park continues to operate without the use of new aviation technologies that could reduce fuel consumption and reduce emissions. Scenario 1 assumes a 5% detour factor for the route network for flights around the world. This factor considers the influence of weather, inefficiency of the route and manoeuvering around the terminal.

In Scenario 1.5, the limited assumes that the N+1 aircraft is introduced into the commercial aviation network in accordance with the information provided in [Nickol,C.,Haller,W., 2016]. This scenario assumes that the N+1 aircraft is introduced on the routes to replace aircraft with similar capacity annual production rates of N+1 aircraft are laid. This scenario limits the production limitations of the N+1 aircraft. Priority is given to routes with 50% more growth than others in between 2016 and 2040. Scenario 1.5 assumes a 3% detour factor for the route network for flights around the world. This implies a more advanced air traffic control system in the future. Scenario 2 assumes that both generations of N+1 and N+2 aircraft are introduced into the commercial aviation network. In this scenario, it is assumed that N+1 and N+2 aircraft are introduced on routes replacing aircraft with similar landing capacity. This scenario limits the introduction of N+1, N+2 aircraft due to production constraints. In this scenario, the limited annual rates of N+2 aircraft production are laid. In this scenario, the limitations on the carrying capacity of N+2 aircraft specified as modest. Scenario 2 assumes a 2% detour factor for the route network for flights around the world. This implies a more advanced airport traffic control system.

Scenario 3 assumes that both generations of N+1 and N+2 aircraft enter the commercial aviation network in accordance with the information provided in [Padalkar Rahul, 2017]. The limits of N+2 production capacity are higher than those used in Scenario 2. Scenario 3 assumes a high annual rate of production of N+2 aircraft after their introduction in 2030. Scenario 3 assumes high performance for N+2 aircraft after their introduction in 2030. Scenario 3 assumes a 2% detour factor coefficient for the route network for flights around the world.

Annual global fuel consumption results were calculated for each scenario described. Table 4.26 provides us with a summa of the annual fuel consumption estimates for all four scenarios studied.

Year	Scenario 1	Scenario 1.5	Scenario 2	Scenario 3
2016	216	216	216	216
2025	295	278	278	261
2030	346	333	319	295
2035	396	379	347	322
2040	442	422	379	348

Table 4.26: The results of modelling the annual global fuel consumption (in billions of kilograms for all scenarios)

Figure 4.100 shows us the same information in graphical form. It is clear that scenario 3 means the use of high-speed introduction of NASA N+2 aircraft has the most positive impact on the environment. Figure 4.101 shows us the annual fuel consumption by commercial aviation for seven regions of the world in the assumptions made for scenario 3. Tendencies indicate that Asia is a region that is expected to have more flights and, therefore, more fuel used in 2040. In Scenario 3, it is expected that the annual fuel consumption used in Asia will increase by 86% from 63 billion kilograms to 117.5 billion kilograms.

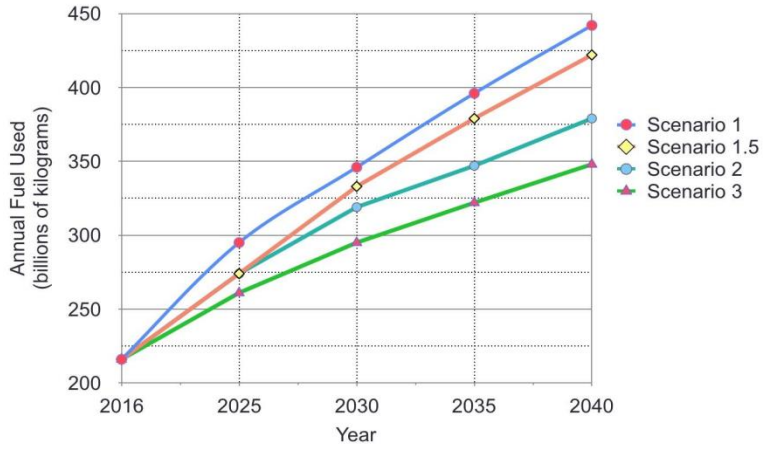


Figure 4.100: Annual global fuel consumption for all simulated scenarios

Figure 4.102 shows us the annual fuel consumption for distinct countries. The graph compares the annual fuel consumption between the US and the BRIC countries. China appears to be the country with the largest change in annual fuel consumption for commercial aviation between 2016 and 2040. Even with the introduction of NASA's N+2 generation of aircraft in 2030, it is expected that in 2040 China will consume 113% more aviation fuel than in 2016 due to the significant growth in aviation operations in the country.

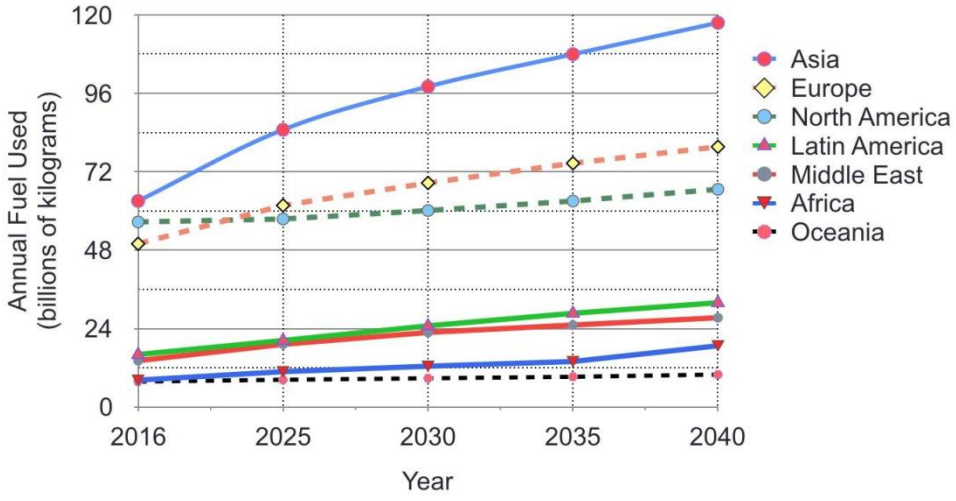


Figure 4.101: Annual projected fuel consumption by region

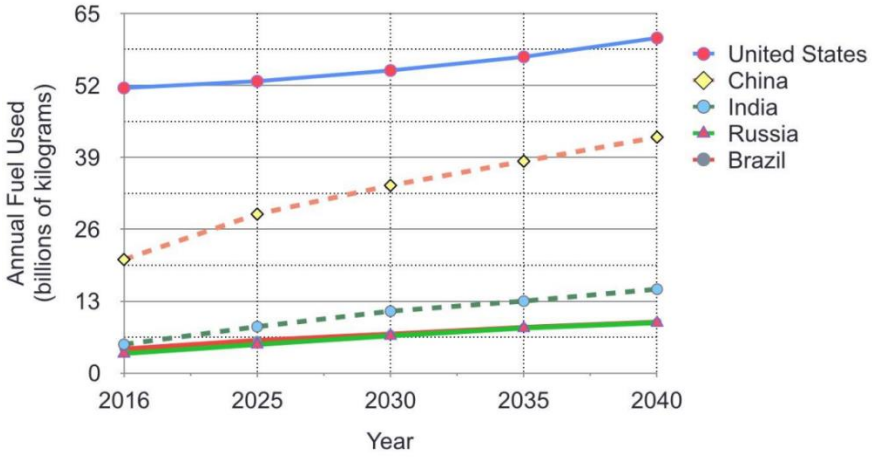


Figure 4.102: Annual fuel consumption for selected countries

Figure 4.103 shows the annual fuel consumption in 2040, which corresponds to each 1x1 degree cell on Earth for scenario 3. The map shows the regions of the world (including airspace corridors) with heavy fuel use. For example, countries being highlighted are China, the European Union, South-East Asia, the Middle East, as four regions where a high concentration of fuel consumption is expected in 2040. The projected reduction in emissions of pollutants for the LTO cycle in 2030, 2035 and 2040 for scenario 3 related to the emission level corresponding to scenario 1.5 is shown in Figure 4.104.

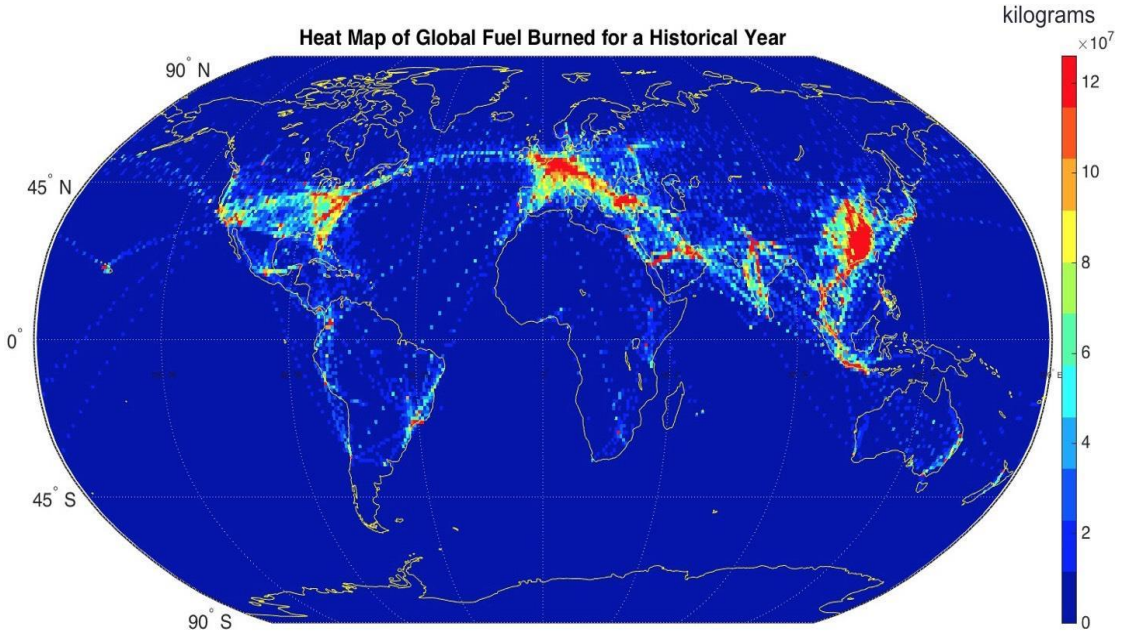


Figure 4.103: Annual fuel consumption for Scenario 3

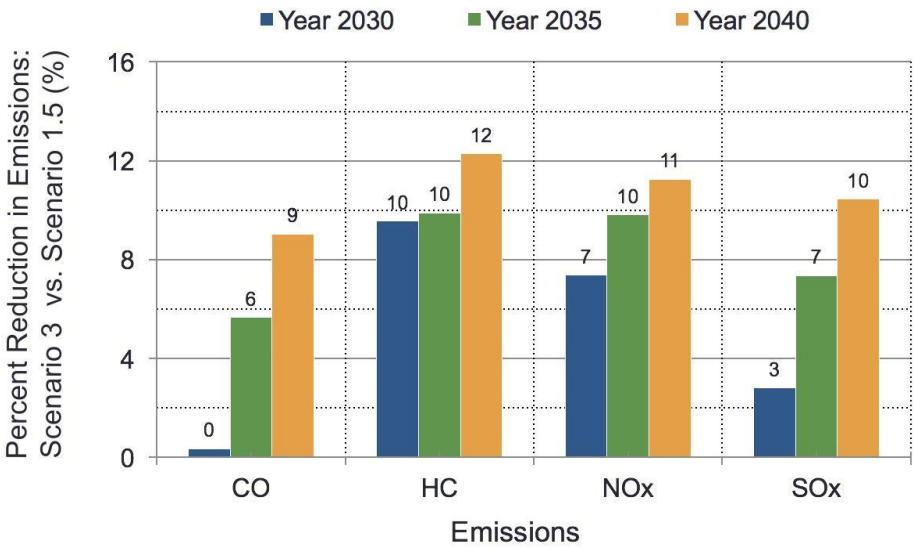


Figure 4.104: Annual emission reductions in the LTO cycle between scenarios 1.5 and 3

Figure 4.105 shows global annual CO_2 emissions for all four scenarios observed during the analysis. The introduction of NASA's N+2 generation aircraft in large numbers (scenario 3) has reduced global CO_2

emissions from aviation activities in 2040 by 17.6% compared to scenario 1.5, i.e. introduce the only aircraft of the generation N+1. In case of bringing into service a large number of N+2 generation aircraft up to 2040, it is possible to reduce CO_2 emissions by 234 billion kilograms per year. Figure 4.106 shows the results of CO_2 emissions for the regions of the world for scenario 3. Figure 4.107 shows the annual CO_2 emissions for distinct countries. The graph compares the annual CO_2 emissions produced by the US and the BRIC countries. China is the country with the largest change in annual fuel consumption for commercial aviation between 2016 and 2040. Even with the introduction of NASA N+2 aircraft in 2030, it is expected that China will produce emissions in 2040 of CO_2 by 113% more than today.

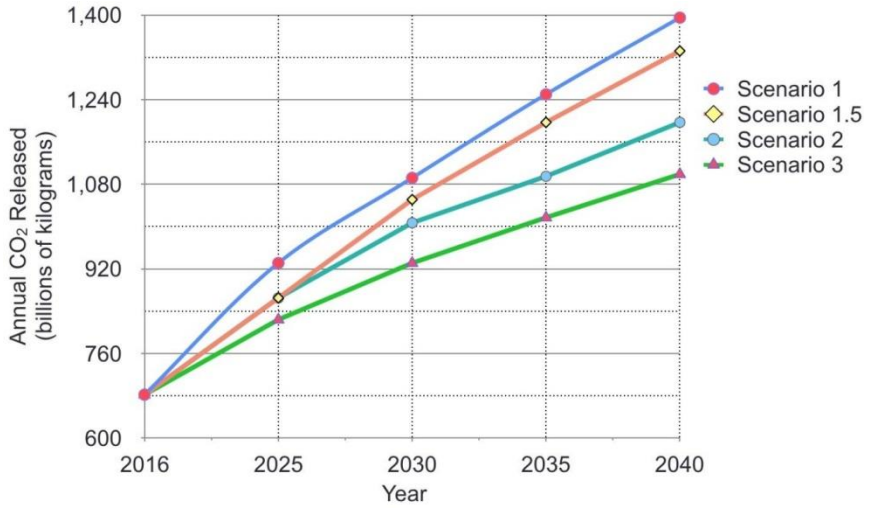


Figure 4.105: Annual CO_2 emissions produced by commercial aviation for all scenarios

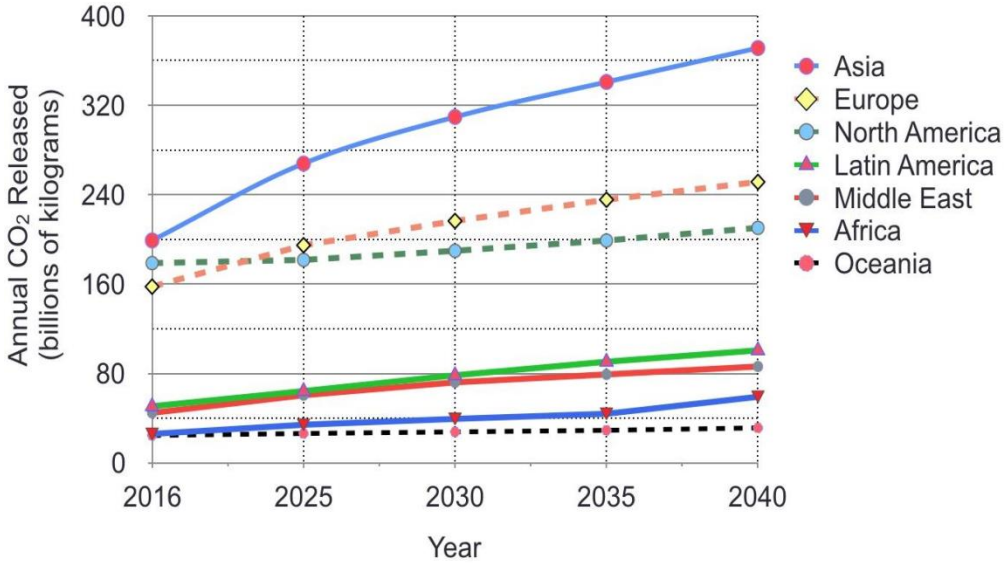


Figure 4.106: Annual CO_2 emissions produced by the regions of the world according to Scenario 3

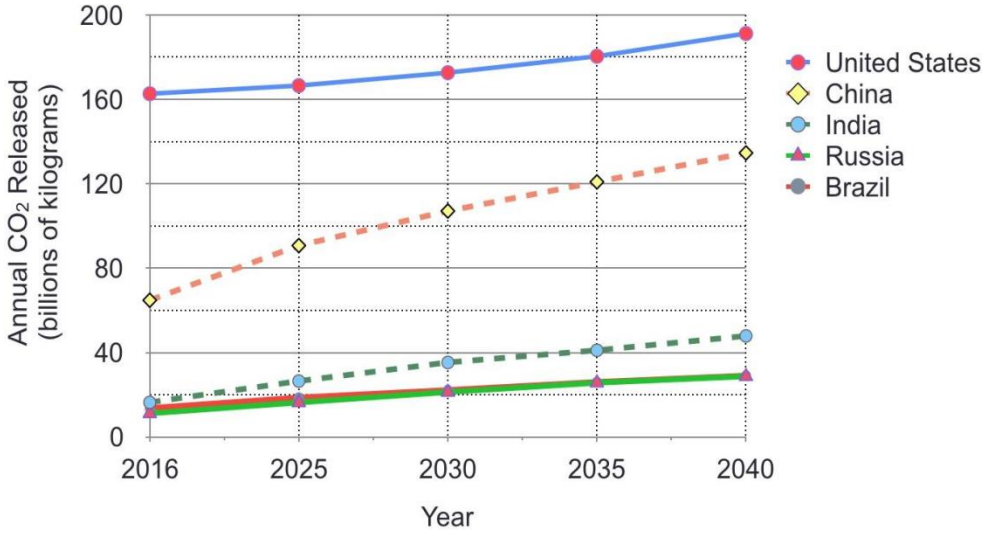


Figure 4.107: Annual CO_2 emissions for selected countries under Scenario 3

Figure 4.108 shows the annual CO_2 emissions in 2040 corresponding to each 1x1 degree cell on Earth for scenario 3. The map shows the world regions (including airspace corridors) with high intensity of CO_2 emissions. For example, the most highlighted countries on the map are China, the countries of the European Union, South-East Asia and the Middle East as regions where a high concentration of CO_2 emissions expected in 2040.

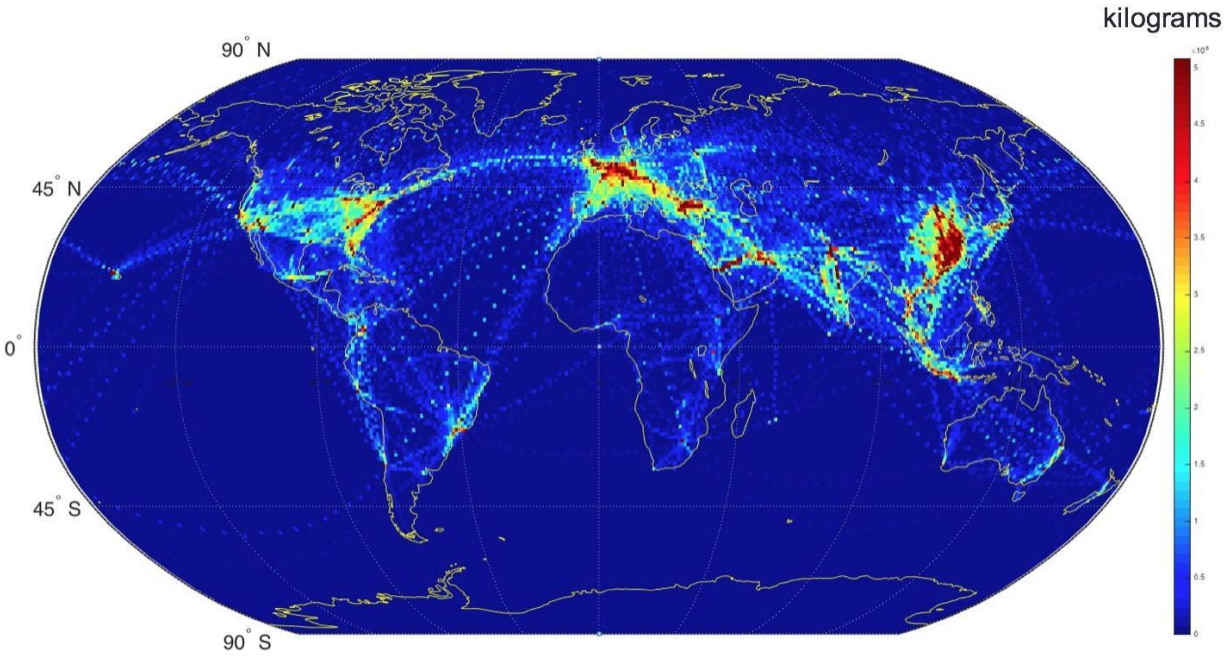


Figure 4.108: Annual CO_2 emissions calculated for each 1 × 1 cell for Scenario 3

Another significant impact on CO_2 emissions worldwide are:

1. The introduction of NASA generation N+2 generation in small quantities (scenario 2) leads to a reduction in annual CO_2 emissions in 2040 by 14.3% compared to scenario 1 and 10.2% compared to scenario 1.5.

2. The introduction of a large number of NASA N+2 generation aircraft (scenario 3) results in a 21.3% reduction in annual CO_2 emissions in 2040 compared to scenario 1 and 17.5% compared to scenario 1.5.

In Figure 4.109 the results of the GDM fuel usage model are compared with the target level of the ICAO specific fuel consumption reduction. The ICAO model assumes a 2% reduction in fuel consumption each year. It is shown that ICAO's technical goal for a 2% reduction in fuel consumption per year yields results similar to those in Scenario 2, so the introduction of NASA N+2 generation in modest quantities since 2030. Scenario 3 provides a higher fuel economy compared to the ICAO technical goal, as shown in Figure 4.109.

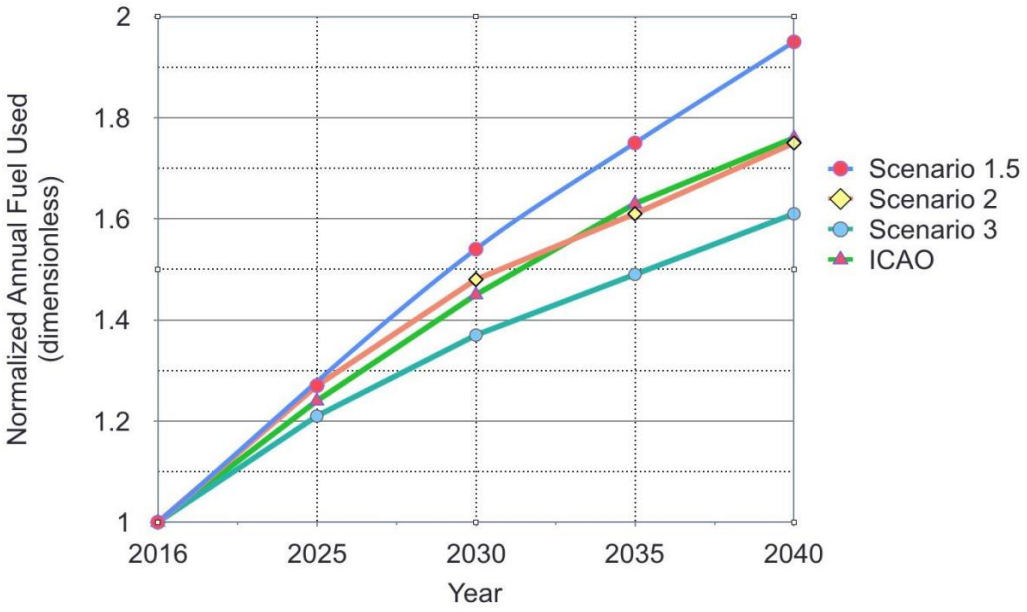


Figure 4.109: Comparison of normalized fuel consumption tendencies for scenarios 1.5, 2, 3 and the goal of ICAO: 2% global annual increase in fuel efficiency

The results of the simulation can be summarized as follows. The introduction of NASA N+2 generation in small quantities (scenario 2) leads to a reduction in annual fuel consumption to 2040 by 14.3% compared to scenario 1 and by 10.2% compared to scenario 1.5. The introduction of a large number of NASA N+2 generation aircraft (scenario 3) results in a 21.3% reduction in annual fuel consumption by 2040 compared to scenario 1 and 17.5% compared to scenario 1.5. Regions of the world that can benefit the most from the operation of NASA's N+2 generation aircraft are regions with faster growth tempo, such as Asia and the Middle East. The 17.5% reduction in fuel consumption, which can be achieved according to Scenario 3 in comparison to Scenario 1.5 indicates the upcoming task of reducing fuel consumption for a large number of aircraft. The effect of the introduction of a large number of N+2 generation aircraft was evaluated In Scenario 3, but at the end of a 10-year production period (2040), only 31% of the world fleet could be replaced by N+2 aircraft. The annual reduction of fuel consumption by 17.5% means saving 74 billion kilograms of aviation fuel. According to the US Environmental Protection Agency, 74 billion kilograms of greenhouse gas emissions are comparable with the amount, which 455 million cars are producing in one year. The introduction of five types of upgraded N+2 aircraft in 2030 could reduce global emissions of CO_2 produced by aviation by 2040, by 21% compared to the baseline scenario and by 17.5% compared to scenario 1.5. This is a significant reduction in the fuel used and CO_2 emissions around the world.

In the work [Ploetner, K. O., et al., 2017] quantitative assessment of the impact of the potential development of aviation technology, increasing of production and improving the infrastructure use on global CO_2 emissions from the fleet of aircraft until 2050 is provided. In the work for the basic scenario, the state of the aviation industry in 2017 is accepted, i.e. the assumption that in the period 2017-2050 reduction technologies for the specific fuel consumption will not be introduced. The numerical model of the global aircraft fleet is used for a quantitative evaluation of the total fuel consumption and reduction of carbon dioxide emissions. There is a prediction of a total reduction in aviation fuel consumption by introducing new aviation technologies by 2050

and it is in the range between 17% and 27% relative to the baseline scenario. The increase in aircraft performance due to the increase in the load factor, passenger capacity and more intensive use of aircrafts further reduces the level of fuel consumption by the aircraft fleet by 7-8% by 2050 relative to the baseline scenario.

The application of retrofit solutions for in-fleet aircraft will reduce the level of fuel consumption by the fleet of aircraft up to 2050 by approximately 3% relative to the baseline scenario. The decrease in regional growth rates income per passenger-kilometer (RPK revenue passenger kilometre) can lead to a reduction in fuel consumption by 6% relative to the baseline scenario by a fleet of aircraft until 2050.

In parallel with holding long-term research aimed at reducing environmental impact at aircraft level, aircraft manufacturers are constantly updating their product line with completely new aeroplane programs and performance enhancement packages for existing production lines. Over the last 10-15 years, new long-term aviation programs, such as the Airbus A380, the Boeing 787, the Boeing 747-8 and the Airbus A350, entered the markets in 2005, 2011, 2012 and 2014 respectively. The reduction in the fuel consumption of the Boeing 787 compared to its predecessor Boeing 767 is about 20%. It is claimed, that the Airbus A350 has a 25% reduction in fuel consumption compared to the current Boeing 777 family. In addition to the introduction of new aviation programs, both Airbus and Boeing will also improve their existing A330 and B777 programs through a more efficient wing design and the use of the latest available engine technologies. As a result, the Airbus A330neo and the Boeing 777-X family (including 777 8/9) will achieve a 13% and 20% reduction in fuel consumption, respectively.

For medium-range aircraft markets, the availability of Geared Turbofan engine technology, which offers promising fuel savings of about 15% [*MTU Aero Engines, Product Leaflet PW1000G*], has led to the launch of new programs such as CSeries Bombardier, Mitsubishi Regional Jet (MRJ), Embraer E-Jet E2, Irkut MS-21 or the improvement of existing aircraft programs, such as the updated versions of the Airbus A320NEO.

Figure 4.110 shows the types of next generation aircraft and the predicted level of fuel efficiency improvement [Randt N. P., Jessberger C., Ploetner K.O., 2015]. However, despite these significant efforts to develop new or modernized aviation programs aiming to improve fuel efficiency, it is clear that the goal of achieving a CO-neutral growth after 2020 will not be achieved. Currently, according to Boeing, more than 14,870 single-aisle planes are in operation and more than 28,140 aircraft are expected to come over the next 20 years, and according to Airbus, an even larger number of 20,600 aircraft are in operation (for 2017) and is expected to increase to 34,900 aircraft (for 2036). [Airbus_Global_Market_Forecast_2017-2036]. Even at the current production rate of about 120 aircraft per month, for the Airbus A320 and Boeing 737 families of aircrafts, the very high level of new and more efficient aircraft entering the market slows the achievement of common ambitious targets for emission reductions at the level of the world aircraft fleet [Ploetner K.O., et al., 2017].

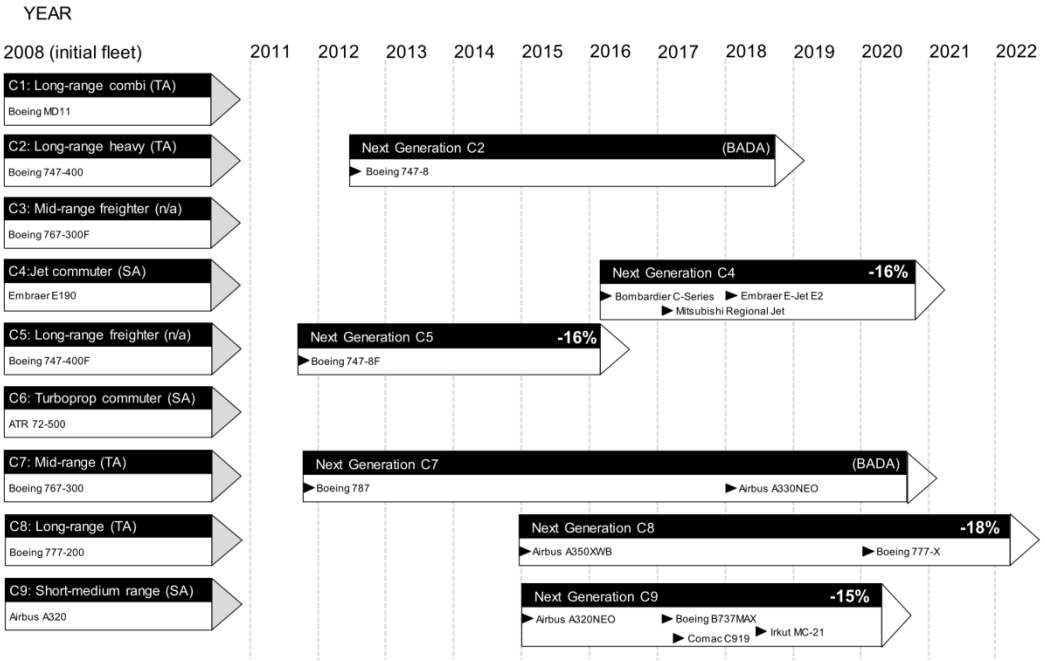


Figure 4.110: Next-generation aircraft types and associated "benefits" in fuel efficiency

The authors identified the most likely scenarios for the use of aviation technology and the introduction of modifications to the design of aircraft, the increase in aircraft production, aircraft performance, growth in RPK (revenue per passenger-kilometre) and changes. This approach allowed the authors to make the quantitative assessment of the effectiveness of various technological and operational improvements regarding global emissions up to 2050, as well as predict total global emissions up to 2050.

For aviation technologies and configurations, three scenarios for fuel consumption reduction accounting at the aircraft level were considered.Scenario 1.1 assumes that the aviation industry can develop and supply new aircraft with reduced fuel consumption (up to 43%) between 2020 and 2035, and 60% reduction in fuel consumption between 2035 and 2050 years.In Scenario 1.2, between 2020 and 2035, fuel consumption is expected to be reduced by 22% for the aircraft, given that most of the current programs will be upgraded [Schilling T., Rötger., T, Wicke, K. 2016], and between 2035 and 2050 it is assumed that the aviation industry can provide a 60% reduction in fuel consumption volume for all aviation programs (48% reduction for scenario 1.3).

The possible effect of the appearance of new aviation technologies on the market is taken into account by three different scenarios for expanding aircraft production. For this study, the production rates and the increase in production of current aircraft programs presented in the work [Leeham, 2017] were used. After 2020, it is assumed that aircraft production increases with the growth of RPK. In case 2.1 it is also assumed that the new aircraft programs will follow the current timeframes for both the B787 or A350XWB, i.e. about six years from the first assembly to full production. In the case of 2.2, all new aircraft programs will be implemented at a more accelerated pace, corresponding to 3 years before full production. In the case of 2.3, all new aviation programs will have a radical time scale corresponding to the time of introduction into production of about one year.

Based on the results until 2025, the baseline and three general emission reduction scenarios were calculated, named asconservative, ambitious and radical. Scenarios were calculated using new aviation programs (cases 1.1-1.3), increasing aviation production (cases 2.1-2.3), increasing aircraft performance (cases 3.1-3.3), changing in regional growth rates of the RPK (case 4) and aircraft modernization technologies (case 5).

The conservative scenario includes incompletion of the SRIA 2035 and 2050 targets for reducing fuel consumption, increasing production, and increasing aircraft performance during the next six years.The ambitious scenario includes incompletion of the SRIA 2035 goals of reducing fuel consumption, expanding production and increasing aircraft performance for three years, and also takes into account modifications and upgrades for the current fleet of aircraft. The radical scenario includes the introduction of new aircraft programs meeting the objectives of the SRIA until 2050, increasing production and increasing the production rate of aircraft (up to one year), reducing the growth rates of regional RPKs to 50%. At the regional level, a stronger transition from air transport to land, as well as modifications and upgrades for the current fleet of aircraft is expected. In addition to the consolidated three scenarios, each case was consistently calculated within each scenario, and a summary of the simulation results for all the sub-variants in each of the scenarios is given in the work [Ploetner, K.O., et al., 2017].Authors also analysed the impact of aviation technologies and production capabilities, possible options for emission reductions at the operational level were, for example, by changing aircraft performance. In case 3.1, the average load factor increases to 95% (from 80.4% in 2015) [IATA, Fact Sheet Industry Statistics, 2017]. In the case of 3.2, the average number of installed sites is increased by 10% for all aircraft programs considering additional fuel consumption. In case 3.3, the average aircraft load (measured by the number of flights per year) is increased by 10%.In case 4, regional RPK growth rates within the EU, North America and Asia have halved between 2017 and 2050, using the initial growth rate provided by Boeing [*Boeing, Boeing Current Market Outlook 2015-2034*] until 2035 with the assumption of unchanged growth rates until 2050. In case 5, decisions were made to reduce fuel emissions with a 4% reduction in fuel consumption for an operating fleet of aircraft.

As shown in Figure 4.111 The introduction of new aviation programs with lower fuel consumption (22% in 2020-2035 and 48% in the period 2035-2050) leads to a significant reduction in fuel consumption in the entire fleet of aircraft for the "Conservative 1" scenario in comparison with the base level after 2035. Increasing the productivity of aeroplanes by increasing the load factors (conservative 2-4) and the average number of installed sites (conservative 3-4) can further decrease of growth in fuel consumption of the fleet of aircraft after 2020.

As the results of modelling show, due to the complex improvement of aircraft, it is possible to reduce fuel consumption of the aircraft fleet in 2024-2025, but after 2025 the simulated aircraft productivity increases will reach their limiting value, therefore the forecasted fuel consumption again begins to increase. This model, based on static aircraft statistics, does not take into account the effect of the reduction in aircraft lifetime due to the increase in the load factor (conservative 4) and therefore does not simulate a reduction in fuel consumption during the renewal of the fleet of aircraft. A similar effect of increasing aircraft productivity can be observed for ambitious and radical scenarios. In the "Conservative 1" and "Conservative 2" scenarios, similar fuel consumption values were achieved for the fleet due to the same load factors in 2050.

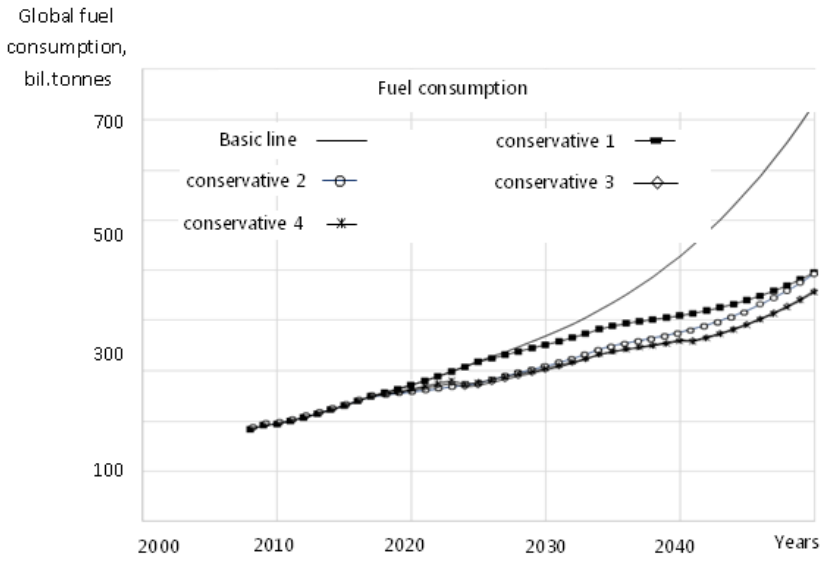


Figure 4.111: Forecast of fuel consumption by the aircraft fleet from 2008 to 2050 for basic and conservative scenarios 1-4

Comparing conservative scenarios 1-4 with the baseline, it can be seen that fuel consumption by the fleet of aircraft can be reduced by 40% (conservative 1) and up to 45% (conservative 4) in 2050. Comparing the results of fuel consumption to 2050 with fuel consumption in 2008, it can be seen that the fuel consumption of the fleet of aircraft will increase 4.5 times for the base level, 2.7 times for "Conservative 1" and 2.5 for "Conservative 4 ".Comparing the scenarios with the lowest level of fuel consumption, such as "conservative 4", "ambitious 5" and "radical 6" with a baseline level, and also with the ATAG goals, as shown in Figure 4.112, it can be seen that even for the "radical 6" scenario, it is impossible to achieve negative fuel consumption on an annual basis.

It can be seen from Figure 4.112 that the requirement to provide a CO-neutral increase can almost be met until 2050 in the case of the "radical 6" scenario. Nevertheless, works to ensure the introduction of promising modifications, with an average reduction in fuel consumption by -43% to 2035 and -60% in the period from 2035 to 2050, for the whole fleet of passenger aircraft from regional turboprops to large long-range aircraft require large costs by the aviation industry. It is estimated in the work [Ploetner, K.O., et al., 2017] that the considered level of improvement in aviation technologies, as well as the slowdown in RPK growth, will not fully meet the ATAG 2050 goal: to cut the total by 2050 the amount of CO_2 emissions compared to the 2005 level. The authors note that to achieve the target level of CO_2 emission reduction, the widespread use of alternative fuels is required.

The emissions from the calculation of the baseline scenario exceed the ATAG target values by 11.7 times in 2050, the "Conservative 4" scenario exceeds the target by 6.4 times and the "ambitious 5" scenario by 5.1 times. Even for the most severe scenario (radical 6), the level of fuel consumption by the fleet of aviation equipment exceeds the objectives of ATAG by 3.8 times. Therefore, it is necessary to carry out studies that will assess the impact of more radical aviation technologies with a higher potential for reducing CO_2 emissions, lower RPK growth rates or renewable "drip" fuels offering a significantly smaller CO_2 footprint compared to conventional jet fuel, and to find ways to overcome the gap between the projected and the target CO_2 emissions of 2050.

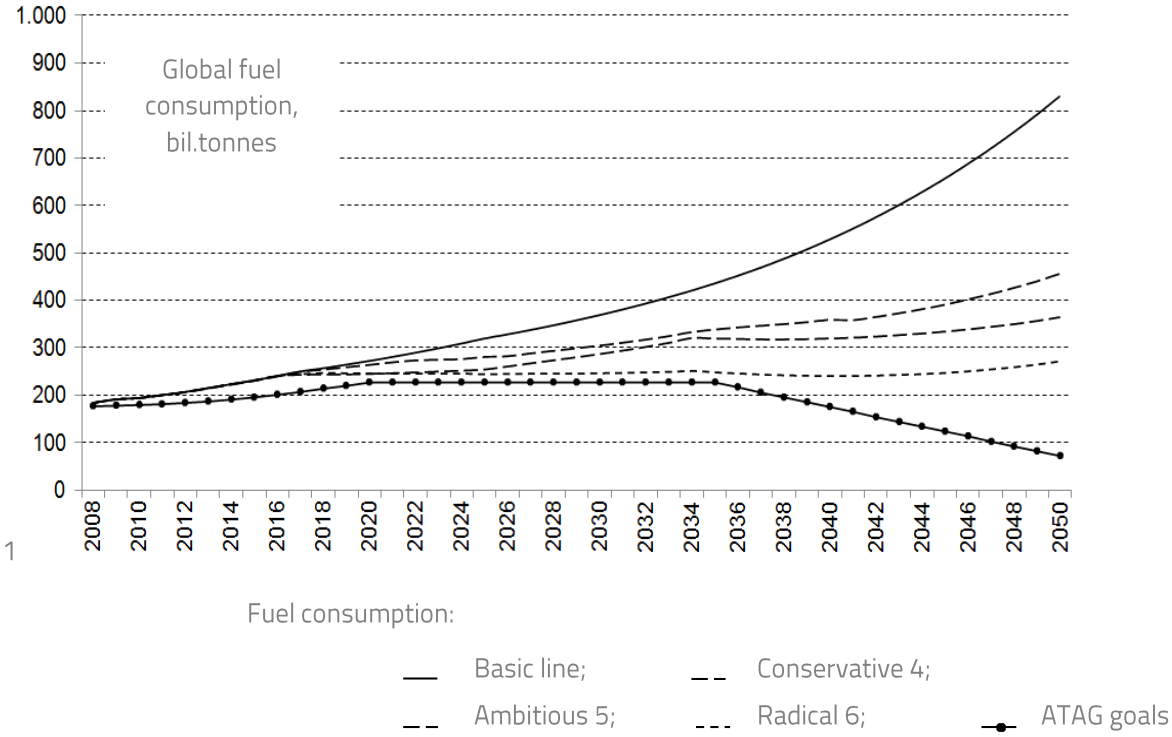


Figure 4.112: Forecast of fuel consumption for the aircraft fleet for the scenarios under study and the target ATAG level period 2008 to 2050

International aviation fuel efficiency is expected to improve through 2050, but measures in addition to those considered in this analysis will be required to achieve ICAO's 2 percent annual fuel efficiency aspirational goal. Sustainable alternative fuels have the potential to make a significant contribution, but sufficient data are not available to confidently predict their availability over the long term. Also, considering only aircraft technology and operational improvements, additional measures will be needed to achieve carbon-neutral growth relative to 2020.

Figure 4.113 shows the estimated excess CO_2 emissions generated per flight that can be attributed to inefficiencies related to overall Air Navigation Services. These excess emissions have decreased by 7% since 2012, with the climb and descent phase decreasing by 6%, the taxi phase by 8% and the en route phase by 7%. It should be noted that the inefficiencies in the individual flight phases are average excess emissions compared to theoretical optima. These theoretical optima are not achievable in reality at the air traffic system level due to safety or capacity limitations. Therefore the excess emissions indicated cannot be reduced to zero, as a certain level of excess fuel burn is necessary if a network system is to be run safely and efficiently.

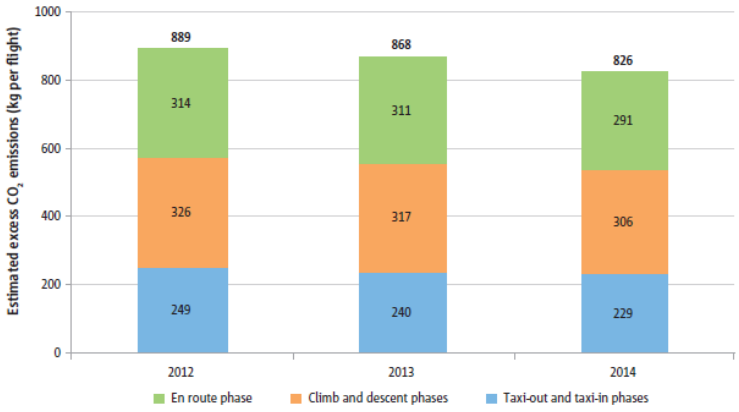


Figure 4.113: Estimated excess CO_2 emissions per flight are decreasing in taxi, take-off, climb/descent and en route phases

FORUM-AE's reference when assessing European progress towards ACARE emissions CO_2& NOx goals is shown in the Figure 4.114. One should also note that NOx emissions are considered either at local level when addressing air quality concern or at global scale when addressing climate change. Still referring to SRIA Vol. 1, Appendix, the timing assumption to progress towards CO_2& NOx goals is the shown in Figure 4.114 also.

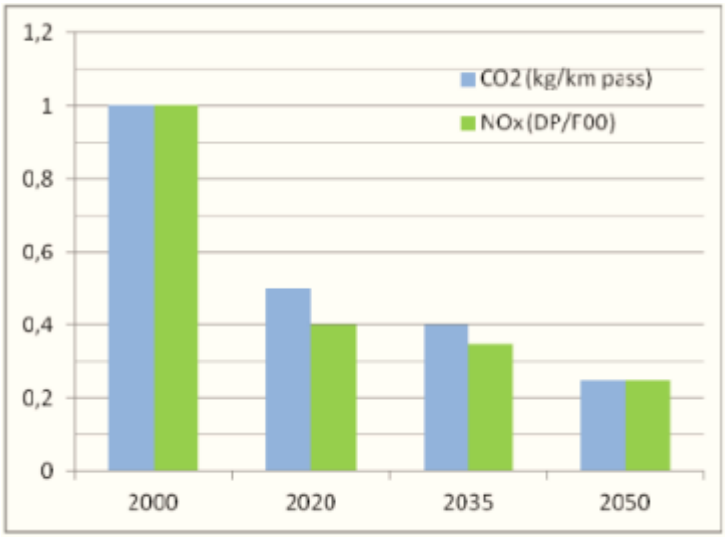


Figure 4.114: ACARE CO_2& NOx goals calendar (using CAEP6 margin for NOx) [FORUM-AE, 2015]

Air traffic CO_2 share will keep increasing unless adapted measures are taken. ACARE 2050 ambitious objectives would permit to mitigate the increase of aviation part in anthropogenic CO_2. If ACARE technology goals were not achieved, if technology improvements were not introduced in the fleet early enough, and if global anthropogenic CO_2 was not growing as much as assumed, the share of aviation could be above 5% in 2050.

ACARE 2050 very challenging CO_2 reduction objective would permit to mitigate substantially the increase of aviation CO_2, with realistic traffic growth assumption. Therefore, it is essential to pursue a tremendous effort at the aircraft level, the engine level and the ATM & flight operation level to progress towards this ambitious goal.

Aircraft/Engine panel of technologies (an exhaustive list would be very long and one can refer to SRIAVol.2 enablers table and FORUM-AE relevant workshops proceedings) must be further and continuously improved or newly introduce both for evolutionary aircraft or engine applications and longer-term disruptive applications.

Unconventional configurations like aircraft equipped with CROR concept or UHBPR concepts must be further developed. Their mitigation potential, complemented with laminar wing benefit, must be maximised and their maturity must be pushed over TRL5, recognizing there is still some gap towards ACARE 2020 CO_2 goal.

The aviation industry is confident that technology, operations and infrastructure measures will provide long-term solutions for aviation's sustainable growth, Figure 4.115. The potential in forecasted period of these three and SAF is shown further, however, the industry recognizes that a global market-based measure (GMBM) is needed to fill any remaining emissions gap. Also in respect to this the State Action Plans on Emissions Reduction (a basket of measures for emission reduction) are a strategic tool for States to plan their activities to address CO_2 emissions from international aviation [ICAO Document 9988, 2019]. States submit their action plans to ICAO on a voluntary basis. The level of detail of the information contained in an action plan will ultimately enable ICAO to compile global progress towards meeting the aspirational goals on

environment set by ICAO Member States. Currently in their action plans, the 14 States selected a total of 218 mitigation measures within the 7 categories of ICAO's basket of measures:

1. **Aircraft-related technology**: 9 measures
2. **Alternative fuels**: 3 measures
3. **Improved Air Traffic Management and infrastructure use**: 79 measures
4. **More efficient operations**: 39 measures
5. **Economic measures**: 4 measures
6. **Regulatory measures**: 15 measures
7. **Airport improvements**: 69 measures



Figure 4.115: Three "in-sector reduction streams" aligned with the Global Coalition for Sustainable Aviation

It is recommended that the States make a "balanced" selection of mitigation measures in their action plan, with measures taken from different categories of ICAO's basket of measures. Accordingly, this basket of measures was used as a reference by the selected States. Of these 218 mitigation measures, 130 (60 %) could be quantified in terms of reduced CO_2 emissions (international emissions and/or co-benefits), and 60 (28%) were quantified in terms of cost. While most measures listed in the action plans had only reached the planning phase and required resources and assistance for implementation, the implementation of 49 measures had already been started, and 25 measures had been completed prior to the submission of the action plan.

Aircraft technology contribution

- Emission reductions from technology: up to ***25% reduction*** in 2050;
- Assumption used: 1.5% efficiency improvement per year for new aircraft entering the fleet.
- Improve fuel efficiency and reduce fuel consumption

Today's aircraft are ~80% more fuel efficient per passenger km than that in the 1960s (Figure 4.19) due to improved fuel efficiency and reduced fuel consumption:

- Reduction in weight is a key factor in reducing fuel burn
- Improvements in
  - propulsion (higher by-pass ratio, GTF, higher turbine temperature),
  - aerodynamics (winglets, foldable wings),

- structural design and materials (additive manufacturing, composites).

The latest generation of aircraft (e.g. A350, B787), powered by more efficient engines, burn about 15-20% less fuel than the aircraft they replace. This impact is seen in the graph below. Fuel burn per 100 passenger kilometers fell by 24% between 2005 and 2017, from 4.4 to 3.4 l/100km, and can be expected to improve further. Further continuous advancements in R&D will be achieved: Novel Aircraft Technology (Blended wing body – Strut-braced wing), Hybrid electric propulsion technology, Hydrogen propulsion. The new generation of aircraft will still be in production in 15-20 years' time. The last airframe off the production lines will be in service approximately 30 years after that, well into the second half of this century. So, there is built-in inertia to a radical "rollover" of the fleet. The introduction of substantially less polluting aircraft from, say 2030-2035, will have a gradual effect, unless there is a fleet replacement surge. This is one reason why the industry talks of a "basket of measures" - all of which are required to reduce net emissions.

Challenges and Opportunities of the aircraft technology contribution:

- Short term (2020-2035), reductions up to 25% or 30% - but harder each time!
- More feasible to implement than "Novel" concepts
- High applicability and compatibility

Operational improvements contribution

- Emission reductions from operational improvements: up to **9% reduction**
- Assumptions considered:
- Electric taxiing systems;
- Removing constraints on vertical and horizontal profiles flight;
- Optimized descent profiles;
- RNAV routes, dynamic airspace configurations, ADS-B use.

Air Traffic Management efficiency has improved since 1999. The Global ATM system is already between 92% and 94% fuel efficient

- At all stages of air travel
- Improvements in:
- More direct flights (horizontal and vertical, free airspace);
- Engine and airframe maintenance;
- Aircraft mass reduction (load factor, materials, waste);
- Altitude and speed optimization;
- Ground operations (one engine on, APU off, solar at gate);
- Airports infrastructures (green building, renewable energies, ACI Airport Carbon Accreditation programme).

Air Traffic Management can influence roughly 6% of aviation's emissions in Europe according to EUROCONTROL's latest Performance Review Report. Currently, the EUROCONTROL Network Manager is coordinating the introduction of "free route airspace" in the upper airspace, which it is estimated has already delivered 2.6 million tonnes of CO_2 emissions savings since 2014. EUROCONTROL is also developing a Joint Action Plan with the industry to encourage more continuous climb and decent operations. This could reduce CO_2 emissions by up to 1.1 million tonnes per year.

The European Commission's Airspace Architecture Study, developed by the EUROCONTROL Network Manager and the SESAR Joint Undertaking, and foresees a potential reduction of up to 13NM in distance flown per flight by 2035, translating into CO_2 savings of 30-60 million tonnes for the period 2019-2035.

ICAO continues to work on operational improvements, first of all in:

- The ICAO Global Air Navigation Plan (GANP);
- The ICAO Aviation System Block Updates (ASBUs);
- ICAO Global guidance documents.

Best practice in this area is the following set of examples:

- Continuous climb and descend;
- Harmonized airspace - Direct routing;
- Big data and AI to optimize operations;
- Engine and airframe maintenance (e.g. engine wash);
- Reducing aircraft mass;
- Fuel (tankering);
- Payload (magazines, seats etc.);
- Reducing engine idling time;
- Emission-free taxiing;
- Reducing APU operational time (e-GSE);
- Training personnel on emission friendly practices.

Challenges and Opportunities in operational improvements:

Challenges

- Wide applicability;
- Cost effective to implement;
- Lower dependency to fleet roll-over;
- Often Reduced A/C maintenance cost;
- Route efficiency;

Opportunities

- Safety;
- Regulatory constraints;
- Constant limitations (weather, equipment, facilities, military activity, traffic);
- Site-specific requirements;
- Limited airport capacity -> Congestion and delays may rise.

Biofuels ort SAFs along with electrification and energy efficiency key to decarbonize the transport sector, Figure 4.116:

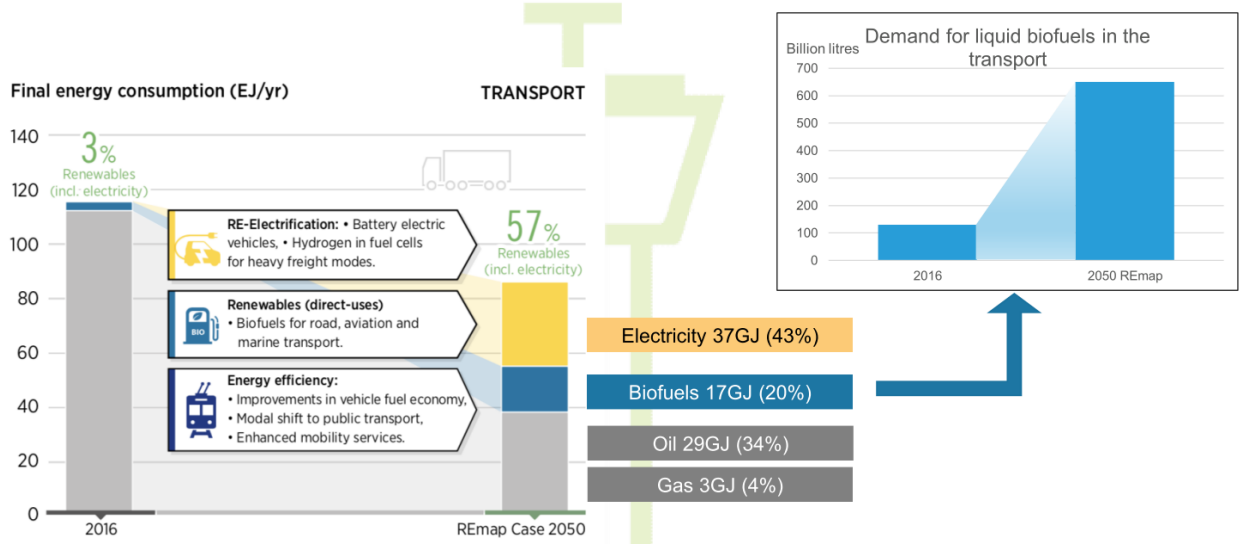


Figure 4.116: Energy consumption by transportation sector

Sustainable Aviation Fuels contribution

- Emission reductions from SAF: up to **41% reduction**, under these assumptions:
- 100%replacement with SAF;
- scenario would require a substantial expansion of the agricultural sector;
- approximately 170 new large bio-refineries to be built every year from 2020 to 2050, at an approximate capital cost of US$15 billion to US$60 billion per year.

There is pent-up demand for SAF but very limited supply at a price point that would attract buyers. Nevertheless, progress is being made. Some EU States are starting to introduce targets for aviation biofuel use, with ambitions up to a 30% share by 2030. United Airlines, KLM and British Airways are investing in sustainable fuels production and are committed to purchasing SAF over the coming years, but this will only cover a small proportion of their flights.

Potential alternative power sources are hydrogen fuel cells and electrofuels, in which water is electrolysed to extract its hydrogen, which is then combined with CO_2 captured from the atmosphere to produce a drop-in liquid hydrocarbon fuel. But both require significant new infrastructure and, as their production processes are energy intensive, this would need to come from renewable sources to make sense. These are potential sustainable fuel sources from the 2030s at the earliest.

USA leads new biofuel technology development, but by 2024 these fuels only provide <2% of biofuel production as the high investment risk of moving from demo- to commercial-scale hampers growth. Biofuels are the best available alternatives:

Oilseed crops on restored land (upgrade biodiesel)

- Europe (rapeseed), China, Americas
- FORBIO project – set aside land in EU

Wood residues (thermochemical routes)

- Uncollected logging residue in Scandinavia
- Unrealised forestry potential in SE Europe

Sugar/Energy cane (1G+2G ethanol plus conversion)

- Brazil, Southern Africa, Caribbean
- Economies from shared 1G/2G process steps
- Future potential enhanced by high-yield energy cane

A key barrier to SAF uptake is their higher cost than fossil jet fuel, Figure 4.117. Greater HEFA production capacity and development of less mature technologies that can use residue and waste feedstocks are needed to increase SAF production and reduce costs, in addition to strong policy measures.

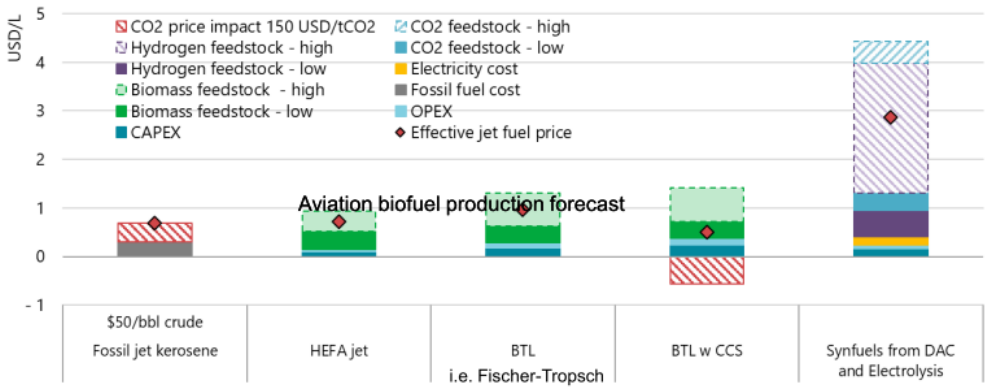


Figure 4.117: A key barrier to SAF uptake is their higher cost than fossil jet fuel

ICAO works on SAFs in framework of Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA):

- Complementary measure to achieve Carbon Neutral Growth from 2020
- The use of CORSIA eligible fuels can reduce airlines' offsetting requirements – CORSIA will incentivize the use of SAF
- Global methodologies have been developed to consider SAF in CORSIA

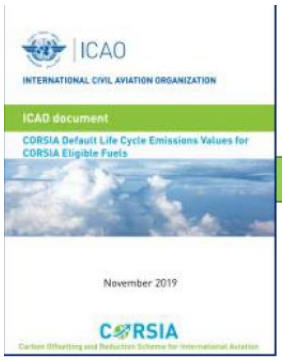
ICAO document "CORSIA sustainability criteria for CORSIA eligible fuels"

First Global Approach to Sustainability agreed by States consists of:

- net GHG emissions reductions of at least 10% on a life cycle basis.
- No feedstock from primary forest deforested areas after 2008
- Work ongoing on other themes:
- Water; Soil; Air; Conservation; Waste and Chemicals; Human and labour rights; Land use rights and land use; Water use rights; Local and social development; and Food security

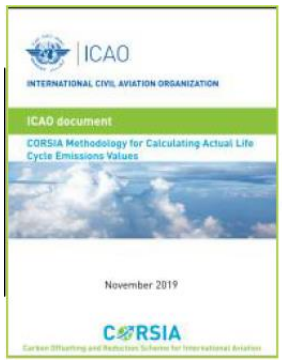
In CORSIA, there are two options to obtain the life cycle emissions of SAF:

ICAO document "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels"



Default emission values, as a function of the feedstocks and conversion processes.

ICAO document "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values"



Allows calculation of specific emissions values to a given SAF

Looking to the future - capacity for SAF production will continue to increase. But one major uncertainty exists: What will the share of SAF production be compared to other fuels? ICAO Vision has a view to include a quantified proportion of SAF use by 2050 [Boshell F., Masuyama T, 2020]. CAAF/2 encouraged States to develop policies that promote the use of SAF, or promote policies that strive to establish a level playing field between aviation and other transportation sectors on the use of sustainable fuels

SAF Challenges & Opportunities:

Opportunities

- High emissions reduction potential

- Wide applicability
- No delay due to of fleet roll-over
- >240,000 flights already operated

Challenges

- Availability of feedstock
- Environmental sustainability
- Cost competitiveness

Renewable Electricity

Prospects of direct electrification of the aircraft (Electric- and hybrid-planes, Figure 4.118) are the following:

- Advantages - lower complexity, fewer moving parts, lower maintenance and operating costs;
- Targeted at short-haul routes

Progress is reached till the date:

- ICAO lists 27 electric planes currently in development (e.g. Boeing, Airbus) and five hybrid-electric models.

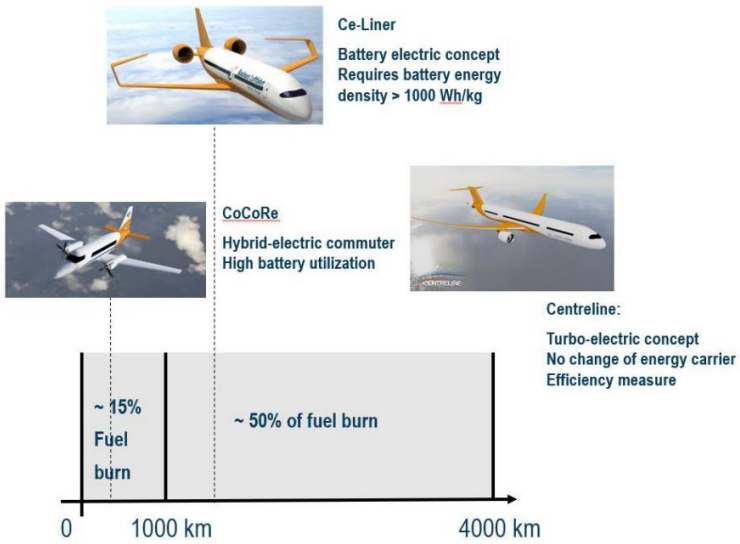


Figure 4.118: Prospects of direct electrification of the aircraft of various flight range

These prospects are provided by key technology challenges:

- Battery energy density – from 300 Wh/kg to + 1 000 Wh/kg;
- Needs an entirely different propulsion system.

Prospect, Progress and Key challenges for indirect electrification (Hydrogen fueled planes, Figure 4.119) [Boshell F., Masuyama T, 2020]:

Prospect

- H_2 directly combusted or use in Fuel Cells for electric propulsion
- Targeted at short and mid-haul routes

Progress

- HyLiner

- ENABLEH2 - Enabling cryogenic Hydrogen

Key challenges

- Hydrogen storage takes substantial space – looking into cryogenic H2
- Increase efficiency of fuel cells
- Not certified by ASTM



Figure 4.119: Hydrogen fueled planes

Synthetic jet fuels are also the example of indirect electrification of the aircraft, their Prospect, Progress and Key challenges [Boshell F., Masuyama T, 2020, Dickson N., 2020, Hupe J., 2020]:

Prospect

- Similar to the existing kerosene
- Fischer-Tropsch route is certified by ASTM and allowed to blend up to 50%
- Use in existing aircrafts, no major changes in design

Progress

- Norsk E-Fuel syncrude plant in Norway -100 ML per year 2025
- German Westküste 100 project 700MW green-hydrogen coupled with CO_2 from cement production
- IRESEN 100 MW green hydrogen plant in Morocco by 2023
- SAF+ Consortium in Canada 4 ML/yr of SAF plant 2025.

Key challenges

- Economics: low cost RE electricity + low cost electrolysis + low cost CO_2 capture
- Sustainability certifications/schemes such as Guarantees of Origin (GO)

Synthetic jet fuels need abundant and affordable renewable electricity:

- Supplying half aviation and shipping fuel demand today would need nearly twice the current global hydrogen production;
- Cost of green hydrogen to be competitive with NG hydrogen ~ USD 1 – 1.6 per Kg H_2 in 2020 and USD 2.5 – 3.2 per Kg H_2 in 2030 ;
- Location matters. Renewable electricity in countries such as Chile, Morocco and New Zealand are competitive with NG-based hydrogen;
- Capacity factor of electrolysers >50%.

4.1.6. Carbon Offsetting and Reduction Scheme for International Aviation

In 2016, the ICAO at 39th Session of its Assembly (Assembly Resolution A39-3) adopted a global market-based measure scheme for international aviation - the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) - to address CO_2 emissions from international aviation. This historic decision is the first time that a single industry sector has agreed to a GMBM in the climate change field. The industry first proposed this measure in 2009 and has supported the ICAO process ever since.

The international standards for the implementation of CORSIA have in the meantime been adopted as an Annex to the Chicago Convention, which all of ICAO's 193 member states must apply from 1 January 2019. CORSIA is the first GMBM for any sector and represents a cooperative approach that moves away from a "patchwork" of national or regional regulatory initiatives through the implementation of a global scheme that has been developed through global consensus among governments, industry, and international organizations.

CORSIA aims to stabilize net CO_2 emissions from international civil aviation at 2020 levels. In 2010, ICAO adopted two Global Aspirational Goals Carbon neutral growth from 2020 onwards (CNG2020) 2% annual fuel efficiency improvement through 2050 (Figure 4.120). Resolution A40-18, paragraph 9: "The Assembly… Requests the Council to continue to explore the feasibility of a long-term global aspirational goal for international aviation, through conducting detailed studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented to the 41st Session of the ICAO Assembly. Assessment of long-term goals should include information from Member States on their experiences working towards the medium term goal".



Figure 4.120: Explore the feasibility of a long term aspirational goal

Main reason for new LTAG is a latest Paris Agreement: "… emission pathways consistent with holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C", explanation of which was done before in Chapter 4.1.4.

The aviation sector is committed to advances in technology, operations and infrastructure to continue to reduce the sector's carbon emissions. Offsetting is not intended to replace these efforts. Nor would CORSIA make fuel efficiency any less of a day-to-day priority. Rather, CORSIA can help the sector achieve its climate targets in the short and medium term by complementing emissions reduction initiatives within the sector. The aviation sector is also committed to reduce its net CO_2 emissions to half of what they were in 2005, by 2050. Achieving this ambitious goal will require continued investment in new technologies and strong support mechanisms for the deployment of Sustainable Aviation Fuels (SAF).

CORSIA complements the other elements of the basket of measures by offsetting the amount of CO_2 emissions that cannot be reduced through the use of basket of measures consisting of technological improvements, operational improvements, and SAF (Figure 4.121) with emissions units from the carbon market. It is estimated that between 2021 and 2035, the international aviation sector would have to offset about 2.5 bln tonnes of CO_2 emissions to achieve carbon neutral growth.

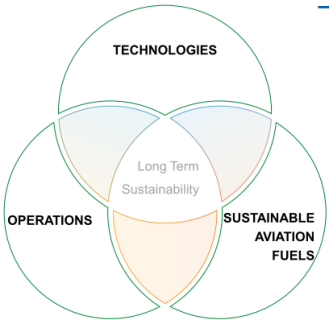


Figure 4.121: Strong synergies in basket of measures to control CO_2 emission in aviation sector

CO_2 emissions directly related to fuel consumption. Global air traffic growth ~ doubles every 15 years ~ x 3.3 times by 2045. There was ~160 Mt of fuel consumed in 2015, by 2045 a fuel consumption ~ x 2.2 - 3.1 times compared to 2015. Continued aviation CO_2 emissions to 2050 will be inconsistent with 1.5 degree emission, Table 4.27.

The industry favors a single, global market-based measure to address CO_2 emissions from international aviation. Many airlines fly into dozens of different countries on a daily basis, with some large airlines serving over a hundred different countries each day; they need to have a single point of accountability. If airlines are subject to a patchwork of national or regional CO_2 taxes, offsetting mechanisms, emissions trading schemes and other carbon pricing instruments, compliance would be unnecessarily complex and costly.

Measures	CO_2	Change in non-CO_2
CORSIA	✔	✘
CO_2 Airplane Standard	✔	✔(if fuel ↓; small ↓ NOx, if ≈ EI), potentially small ↑ in contrails
Operational improvements	✔	✔(if fuel ↓; small ↓ NOx, if ≈ EI)
Lower C footprint SAF	✔	✔ reduced aromatics, S in fuel: decreased contrails, decreased direct negative RF from S aerosol, unknown changes in aerosol – cloud interactions
Carbon neutral synthetic fuels	✔	

Table 4.27: Ongoing and potential future mitigation measures

Offsetting allows a company to compensate for its emissions by financing a reduction in emissions elsewhere. While carbon offsetting does not require companies to reduce their emissions "in-house", it provides an environmentally effective option for sectors where the potential for further emissions reductions is limited. There are many ways to achieve CO_2 reductions that can be used as offsets, many of which bring other social, environmental or economic benefits relevant to sustainable development.

Offsetting and carbon markets have been a fundamental component of emissions reduction policies and continue to be an effective mechanism to underpin action against climate change. Offsetting is also more effective than a tax, as a carbon tax merely requires companies to pay for their emissions, without any guarantees that the payment will lead to any emissions reductions.

Phased implementation for the CORSIA

The 39th and 40th Session of the ICAO Assembly introduced approach, which is based on the use of a phased implementation for the CORSIA (Figure 4.122) to accommodate the special circumstances and respective capabilities of States, in particular developing States, while minimizing market distortion, as follows:

- *Pilot phase applies from 2021 through 2023* to States that have volunteered to participate in the scheme.
- *First phase applies from 2024 through 2026* to States that voluntarily participate in the pilot phase, as well as any other States that volunteer to participate in this phase.
- *Second phase applies from 2027 through 2035* to all States that have an individual share of international aviation activities in RTKs in year 2018 above 0.5 per cent of total RTKs or whose cumulative share in the list of States from the highest to the lowest amount of RTKs reaches 90 per cent of total RTKs, except Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs) unless they volunteer to participate in this phase.



Figure 4.122: Phases of CORSIA implementation [ICAO CAEP/10Meeting, 2016]

Starting in 2022, the Council will conduct a review of the implementation of the CORSIA every three years, including its impact on the growth of international aviation, which serves as an important basis for the Council to consider whether it is necessary to make adjustments to the next phase or compliance cycle and, as appropriate, to recommend such adjustments to the Assembly for its decision [ICAO 39th Assembly,2016, ICAO Annex 16, 2019]. ICAO Member States participating in CORSIA need to ensure that their aeroplane operators comply with the CORSIA *offsetting requirements* every three years, in addition to annual CO_2monitoring, reporting and verification (MRV) [ICAO CAEP/10Meeting, 2016].

How to calculate CO_2 offsetting requirements?

Operator's annual emissions X Growth Factor = CO_2 offsetting requirements

The Growth Factor changes every year taking into account both the sectoral and the individual operator's emissions growth, Figure 4.123 [ICAO CAEP/10Meeting, 2016].. The Growth Factor is the percent increase in the amount of emissions from the baseline to a given future year, and is calculated by ICAO.

After the calculation of the offsetting requirements to be attributed to an aeroplane operator:

- The operator reports the use of CORSIA Eligible Fuels for the compliance period.
- The State deducts the benefits from the use of CORSIA Eligible Fuels and informs the operator's final offsetting requirements for the 3-year compliance period.
- The operator purchases and cancels eligible emissions units equivalent to its final offsetting requirements for the compliance period.
- The operator provides a validated Emissions Units Cancellation Report to the State, who checks the Report and informs ICAO [ICAO CAEP/10Meeting, 2016].

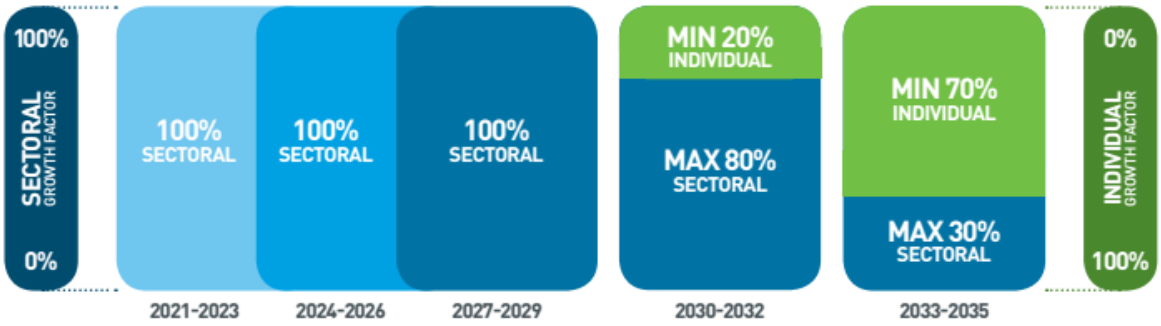


Figure 4.123: Calculation CO_2 offering requirements [ICAO CAEP/10 Meeting, 2016]

How does an aeroplane operator monitor CO_2 emissions?

An aeroplane operator shall monitor and record its fuel use from international flights in accordance with an eligible monitoring method approved by the State to which it is attributed, and shall use the same eligible monitoring method for the entire 3-year compliance period, Figure 4.124. An aeroplane operator can choose from five different eligible methods for fuel use monitoring. The methods are equivalent, there is no hierarchy for selecting a method. An aeroplane operator may choose to use the ICAO CORSIA CO_2 Estimation and Reporting Tool (CERT), accessible through the ICAO CORSIA website [ICAO CAEP/10Meeting, 2016].

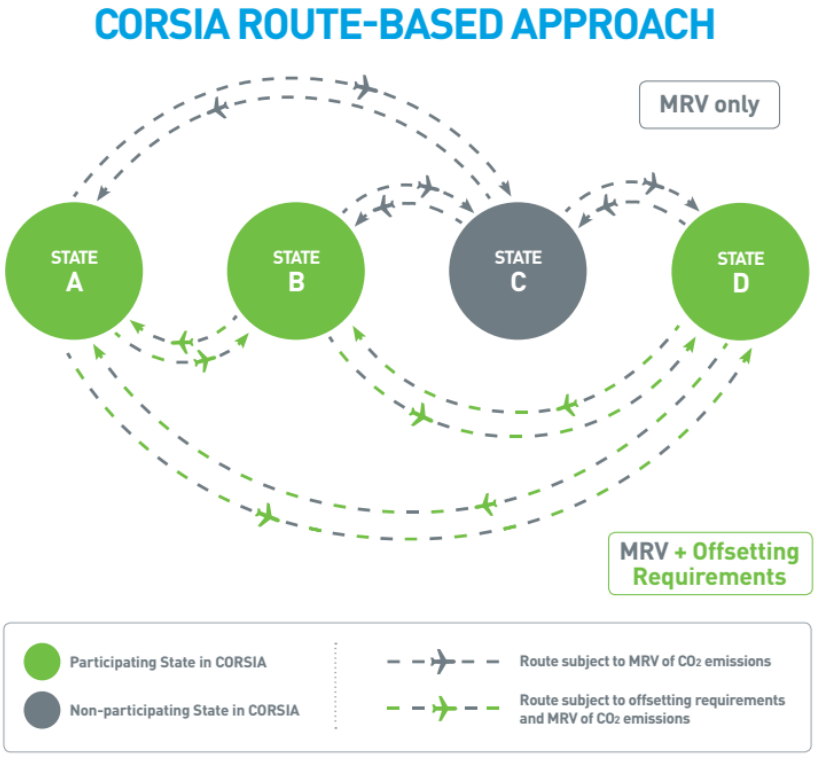


Figure 4.124: CORSIA route-based approach [ICAO CAEP/10Meeting, 2016]

CORSIA implementation

The success of the implementation of CORSIA relies on the establishment of a robust and transparent monitoring, reporting and verification (MRV) system, which includes procedures on how to monitor the fuel use, collect data and calculate CO_2 emissions; report CO_2 emissions data; and verify CO_2 emissions data to ensure accuracy and avoid mistakes [ICAO Annex 16, 2019].

The implementation of CORSIA required a "package" of CORSIA-related SARPs and guidance which comprise of three distinct but interrelated components:

a) Annex 16, Volume IV, which provides the required actions by States and aeroplane operators (the "what" and "when") to implement CORSIA [ICAO Annex 16, 2019,ICAO Environmental Report 2016];

b) Environmental Technical Manual (Doc 9501), Volume IV, which provides the guidance on the process (the "how") to implement CORSIA [ICAO Annex 16, 2019,ICAO Environmental Report 2019]; and

c) Five CORSIA Implementation Elements, which are reflected in 14 ICAO documents and are approved by the Council prior to their publication [ICAO Annex 16, 2019].

These ICAO documents are directly referenced in Annex 16, Volume IV and are essential for the implementation of CORSIA. The Council adopted the First Edition of Annex 16. Volume IV in June 2018. Following its adoption, the First Edition of Annex 16, Volume IV became applicable on 1 January 2019. The First Edition of the Environmental Technical Manual (Doc 9501), Volume IV was issued under the authority of the ICAO Secretary General in August 2018. This manual will be periodically revised to make the most recent information available to administrating authorities, aeroplane operators, verification bodies and other interested parties in a timely manner, aiming at achieving the highest degree of harmonisation possible.

The ICAO Council has been undertaking work, with the contribution of the CAEP, on the development of the five CORSIA Implementation Elements, namely:

- *CORSIA States for Chapter 3 State Pairs* is the list of States participating in CORSIA and will be used to define route-based emissions coverage every year from 2021 onwards;
- *ICAO CORSIA CO_2 Estimation and Reporting Tool (CERT)* aims to simplify the estimation and reporting of CO_2 emissions from international flights for those operators with low levels of activity to fulfil their monitoring and reporting requirements under CORSIA (for more details, see the dedicated article in this chapter);
- *CORSIA Eligible Fuels* cover aviation fuels used for the purposes of CORSIA to reduce the offsetting requirements of aeroplane operators (for more details, see the dedicated article in this chapter);
- *CORSIA Eligible Emissions Units* are emissions units from the carbon market that can be purchased by aeroplane operators to fulfil the offsetting requirements under CORSIA (for more details, see the dedicated article in this chapter); and
- *CORSIA Central Registry (CCR)* is an information management system that will allow the input and storage of CORSIA-relevant information reported by States, as well as calculations and reporting by ICAO, in accordance with the CORSIA MRV requirements as contained in the Annex 16, Volume IV (for more details, see the dedicated article in this chapter).

In June 2018, to ensure that *No Country is Left Behind*, the Council endorsed the ICAO ACT-CORSIA Programme (Assistance, Capacity-building and Training for the CORSIA), emphasizing the importance of a coordinated approach under ICAO to harmonize and bring together all relevant actions and promote coherence to capacity building efforts related to CORSIA implementation. By the end of June 2019, CORSIA buddy partnerships under ACT-CORSIA had been established, involving 15 donor States and 98 recipient States [ICAO Annex 16, 2019].

CORSIA emissions unit eligibility criteria

Program Design Elements. At the program level, ICAO should ensure that eligible offset credit programs meet the following design elements:

1. Clear Methodologies and Protocols, and their Development Process.

2. Scope Considerations.
3. Offset Credit Issuance and Retirement Procedures.
4. Identification and Tracking.
5. Legal Nature and Transfer of Units.
6. Validation and Verification procedures.
7. Program Governance.
8. Transparency and Public Participation Provisions.
9. Safeguards System.
10. Sustainable Development Criteria.
11. Avoidance of Double Counting, Issuance and Claiming.

Carbon Offset Credit Integrity Assessment Criteria: There are a number of generally agreed principles that have been broadly applied across both regulatory and voluntary offset credit programs to address environmental and social integrity. Eligibility criteria should apply at the program level, as the expertise and resources needed to develop and implement ICAO emissions criteria at a methodology and project level is likely to be considerable.

Eligibility Criterion: Carbon offset programs must generate units that represent emissions reductions, avoidance, or removals that are additional:

1. Carbon offset credits must be based on a realistic and credible baseline.
2. Carbon offset credits must be quantified, monitored, reported and verified.
3. Carbon offset credits must have a clear and transparent chain of custody within the offset program.
4. Permanence.
5. A system must have measures in place to assess and mitigate incidences of material leakage.
6. *Criterions* Are only counted once towards a mitigation obligation.
7. Carbon offset credits must represent emissions reductions, avoidance, or carbon sequestration from projects that do no net harm [ICAO Environmental Report 2019].

Environmental integrity

There are many ways to achieve CO_2 reductions that can be used as offsets (Figure 4.124), many of which bring other social, environmental or economic benefits relevant to sustainable development (based on long term sustainable solutions, holistic approach and interdependencies with other sectors). Such offsets can be sourced from various types of project activities, including, for example, wind energy, clean cook stoves, methane capture, forestry and other emissions-reducing or avoidance projects.

To ensure the environmental integrity of CORSIA, the ICAO Council will adopt a list of emissions units that can be used for compliance. The Council's decision will be informed by a recommendation from the Technical Advisory Body and guided by environmental criteria to guarantee that emissions units deliver the desired CO_2

reductions. The criteria are based on principles commonly applied under existing trading mechanisms and well-accepted carbon offset certification standards:

- A key requirement is that the greenhouse gas reduction or removal used as an offset be 'additional' to business-as-usual activity. Offsets must also represent a permanent reduction of emissions that cannot be reversed. Similarly, an activity that generates offsets should not result in unintended increases in emissions elsewhere.
- To quantify the greenhouse gas reduction benefits from an offsetting project, a baseline must be determined to represent what would have happened if the project had not been implemented. Emissions reductions will need to be quantified using accurate measurements, valid protocols, and be audited.
- Emissions Units Programs will need to demonstrate that they have procedures in place to track units and to avoid that an emissions reduction is counted more than once towards attaining climate change mitigation.
- Emissions units programs will also need to have safeguards in place to address environmental and social risks.

It is forecast that CORSIA will mitigate around 2.5 billion tonnes of CO_2 between 2021 and 2035, which is an annual average of 165 million tonnes of CO_2. This is equivalent to the annual CO_2 emissions from the Netherlands, all sectors included.

Reporting of emissions

All operators with annual emissions greater than 10,000 tonnes of CO_2 are required to report their emissions on an annual basis, with monitoring starting from 1 January 2019 (international flights only). Operators must keep track of their fuel use for each individual flight in order to calculate the CO_2 emissions. They will have to apply one of the five approved fuel use monitoring methods. In certain circumstances, however, operators may be eligible to use simplified monitoring and estimate their emissions using the CERT, an estimation tool developed in ICAO.

In order to guarantee the accuracy of the data reported by operators, annual emissions reports will need to be verified by an independent third-party verification body, prior to submission to the state. Verification bodies will have to be accredited to ISO 14065 and CORSIA-specific requirements.

Aggregated emissions will be communicated by states to ICAO, which will publish the total emissions from individual operators, and total emissions by all operators aggregated on each state-pair.

Offsetting requirements

Offsetting requirements will apply from 2021. At the end of each 3-year compliance period, operators will have to demonstrate that they have met their offsetting requirements by cancelling the appropriate number of emissions units. In order to take into account the special circumstances and respective capabilities of states, ICAO member states agreed to implement offsetting requirements in phases:

- From 2021 until 2026, only flights between states that volunteer to participate in the pilot and/or first phase will be subject to offsetting requirements.
- From 2027, all international flights will be subject to offsetting requirements.

The map in Figure 4.125 shows states which have volunteered as of 1 September 2019 (in green) and states from/to which flights are expected to be exempt after 2027 (in yellow).However, flights to and from Least Developed Countries (LDCs), Small Island Developing States (SIDS), Landlocked Developing Countries (LLDCs) and states which represent less than 0.5% of international RTK will be exempt from offsetting requirements, unless these States participate on a voluntary basis.

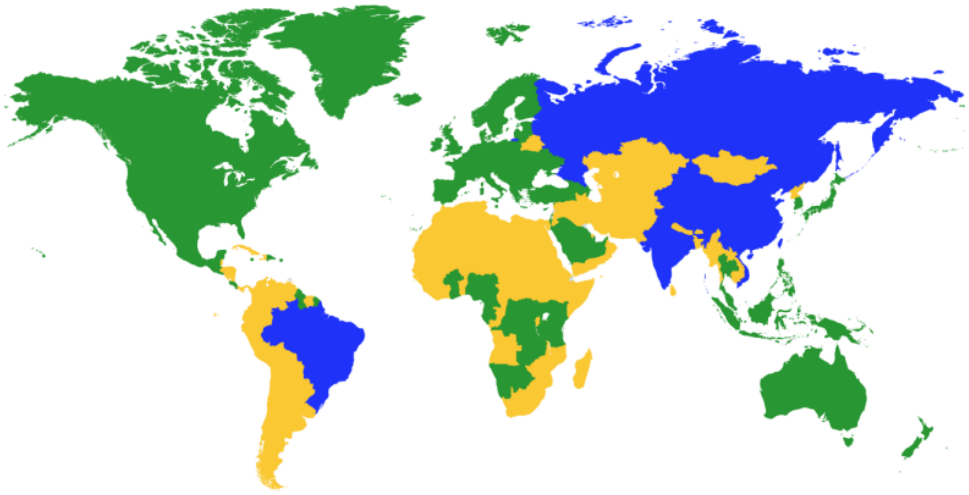


Figure 4.125: World map show in green the States which have volunteered in CORISA (1 September 2019) and in yellow the States from/to which flights are expected to be exempt after 2027

4.1.7. Future SST environmental impact

Over the last decades, the increasing globalization and the associated need for substantially shortened travel times has led to public and privately-funded development of supersonic aircraft. Supersonic transportation (SST) is focused on making the planet dramatically more accessible through supersonic flight. At the beginning a small number of SST aeroplanes is expected to be flying a limited number of business jet airport-pairs and a limited number of commercial air transport airport city-pairs, Figure 4.126. Dubai and London Heathrow are expected to be the two busiest airports, accounting for 7% and 6%, respectively, of daily SST movements.

The potential consumers for supersonic business jets (SSBJs) include corporate flight departments, government agencies, private individuals, charter companies and fractional companies. The passengers' willingness to pay and the service quality they demand is qualitatively presented in Figure 4.127. The figure potentially indicates a small size supersonic aircraft market gap in the overall market. A recent study [Liebhardt B., 2011] summarizes that the market demand for SSBJ is around 20 units per year. However, sufficient demand is neither certain nor verifiable. It is also noted that there are various operational modes for SSBJ class aircraft, but a one-dimensional market will not suffice to realize a growth. During the three decades, there have been a total of 22 activities (six university studies, eight industry studies and eight NASA studies) on the subject of SSBJ. In view of the soon to be expected market entry of the SSBJ Aerion AS21 (triple-engine configuration with supersonic natural laminar flow) and existing plans for commercial SST aircraft with a payload of more than 100 passengers, the ICAO needs to define standards for the advent of this new generation of supersonic aviation. The standardization and rule-making can be roughly subdivided into two major challenges: 1) the sonic boom and its impact on human beings and the environment and 2) the landing and take-off noise and emissions.

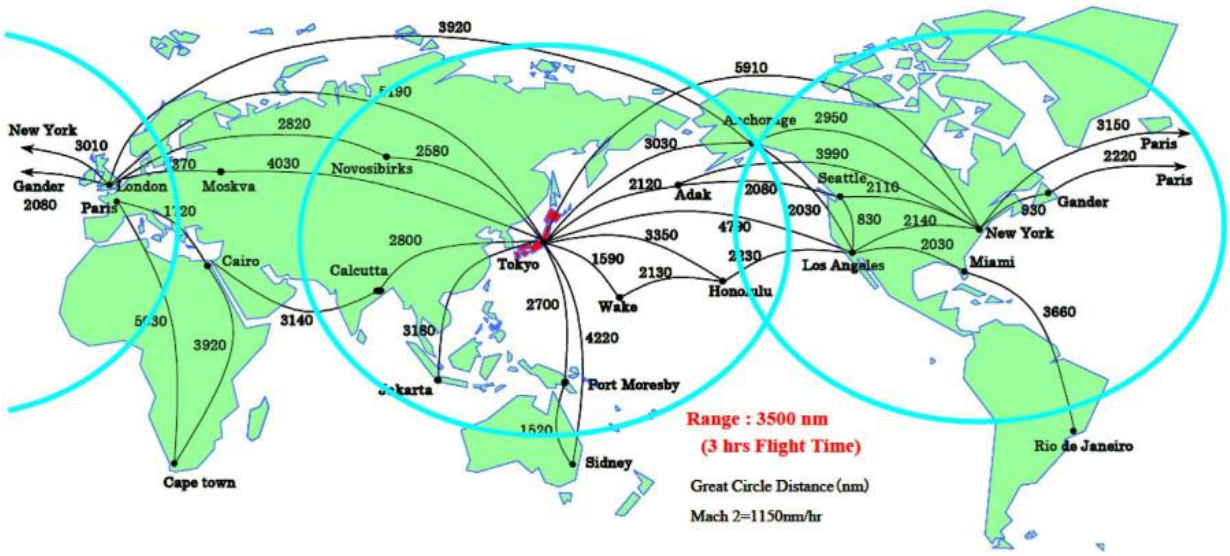


Figure 4.126: Great cycle distance between major cities [Horinouchi S., 2005]

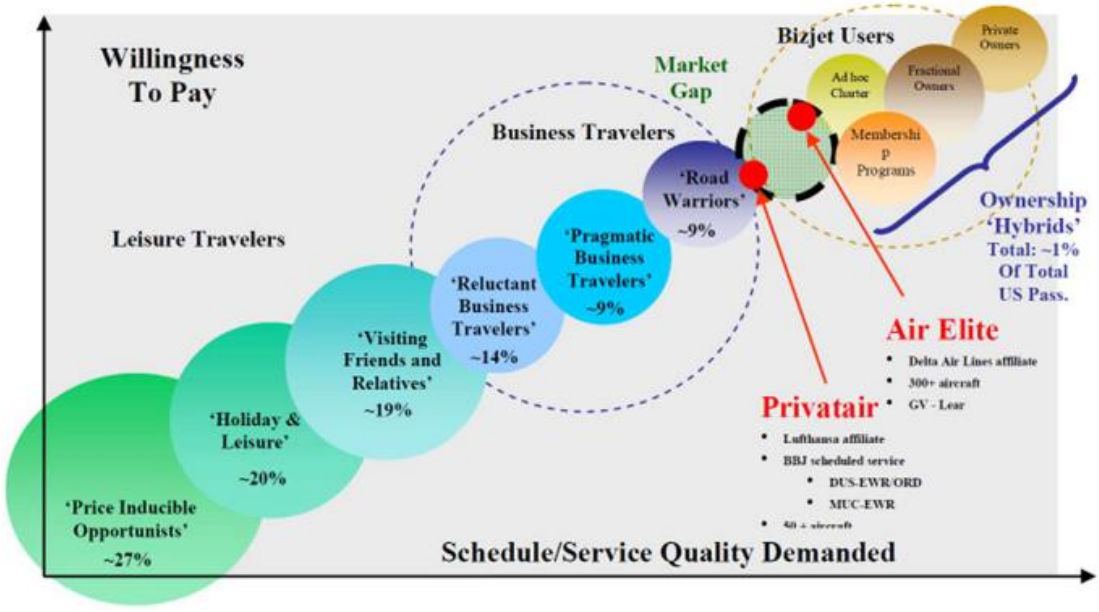


Figure 4.127: Potential size of the supersonic passenger market [Welge H., Nelson C., Bonet J., 2010]

Concorde and Tupolev-144 were the first SST vehicles in civil aviation sector (Figure 4.128), they were powered by turbojet engines with afterburners, which led to high fuel burn and takeoff noise. They both failed commercially due to their high operational costs, safety and operating restrictions linked to its explosive sonic boom, which could reach up to 109 perceived level decibels (PLdB) for Concorde.

Advances in propulsion technologies, materials, and aerodynamic design capabilities mean the next generation of civil supersonic aeroplanes (SST 2.0) will be far more environmentally responsible than their predecessors. New technologies will allow stricter requirements to be set for supersonic aircraft in the longer term, but these aircraft also will be able to leverage other measures to reduce their environmental impact. Many manufacturers (in USA, Europe and Japan), including those with an interest in supersonic aircraft, are taking active steps to help spur growth of the nascent sustainable aviation fuels industry. Supersonic engines are being designed to accommodate drop-in sustainable fuels as readily as subsonic engines. In addition, market-based measures such as ICAO's Carbon Offsetting and Reduction Scheme for International Aviation

and optimized operational procedures also will play their part to ensure aviation meets its climate commitments.

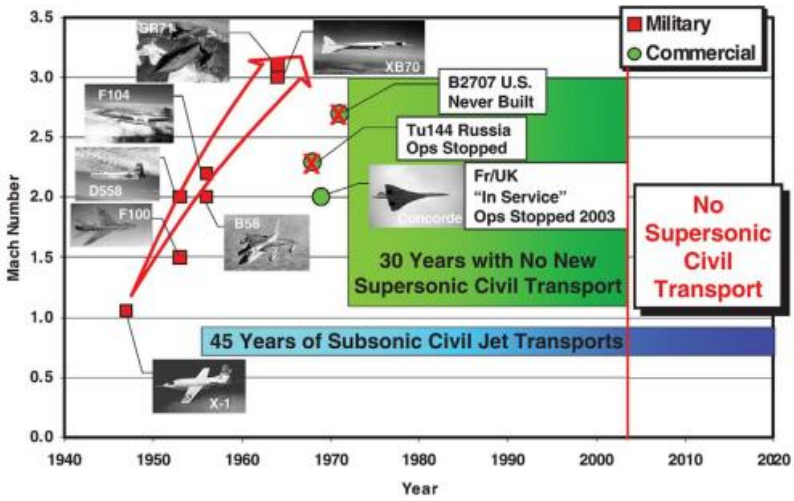


Figure 4.128: Supersonic aircraft progress [Henne P.A., 2005]

Almost two decades have passed, since the last civil supersonic flight with the Concorde, and accordingly there have been few civil research activities on this topic in this time frame. Recently, the NASA has illustrated the most important research and industrial activities around the world on civil supersonic aircraft (Figure 4.129). NASA is developing the X-59 Quiet Supersonic Technology research X-plane in partnership with Lockheed Martin, which is intended to create a sonic "thump" to approximate sounds that may be produced by future large, quiet supersonic aircraft. Community response testing with the X-59 is expected to begin in 2022. Figure 4.130 is showing the roadmap for supersonic research activities at NASA.

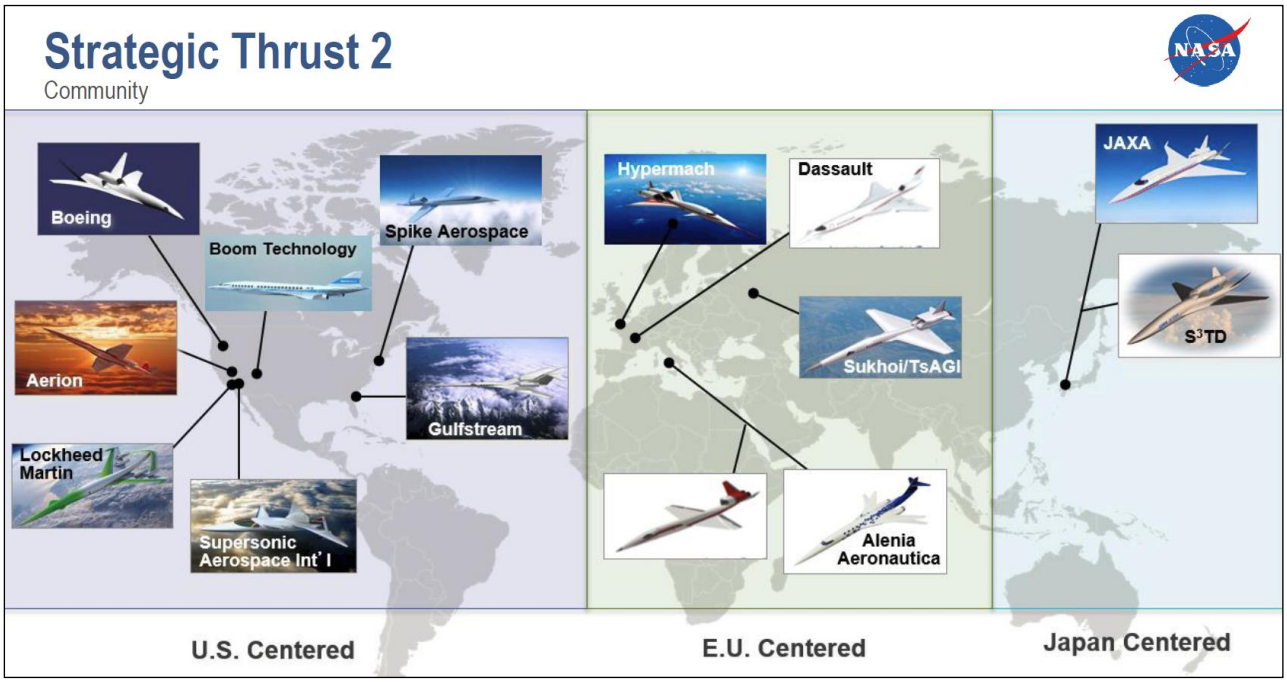


Figure 4.129: Illustration of the industrial and academic activities on supersonic aircraft around the world by NASA [Coan P., 2016]

In order to improve the unacceptable situation, the FAA has taken action and recently (March 2020) published the notice of proposed rulemaking (NPRM) for the noise certification of supersonic aircraft [US DOT FAA 14 CFR Parts 21 and 36, 2020]. The rules of the NPRM can be applied to business jets with a MTOW up to 150,000 lbs and a design speed up to Mach 1.8. Moreover, the proposed standard explicitly allows the usage of variable noise reduction systems (VNRS) for the change of thrust or configuration during LTO. The introduced noise limits in the NPRM are halfway between Chapter 4 and Chapter 14 of ICAO Annex 16 Vol I.

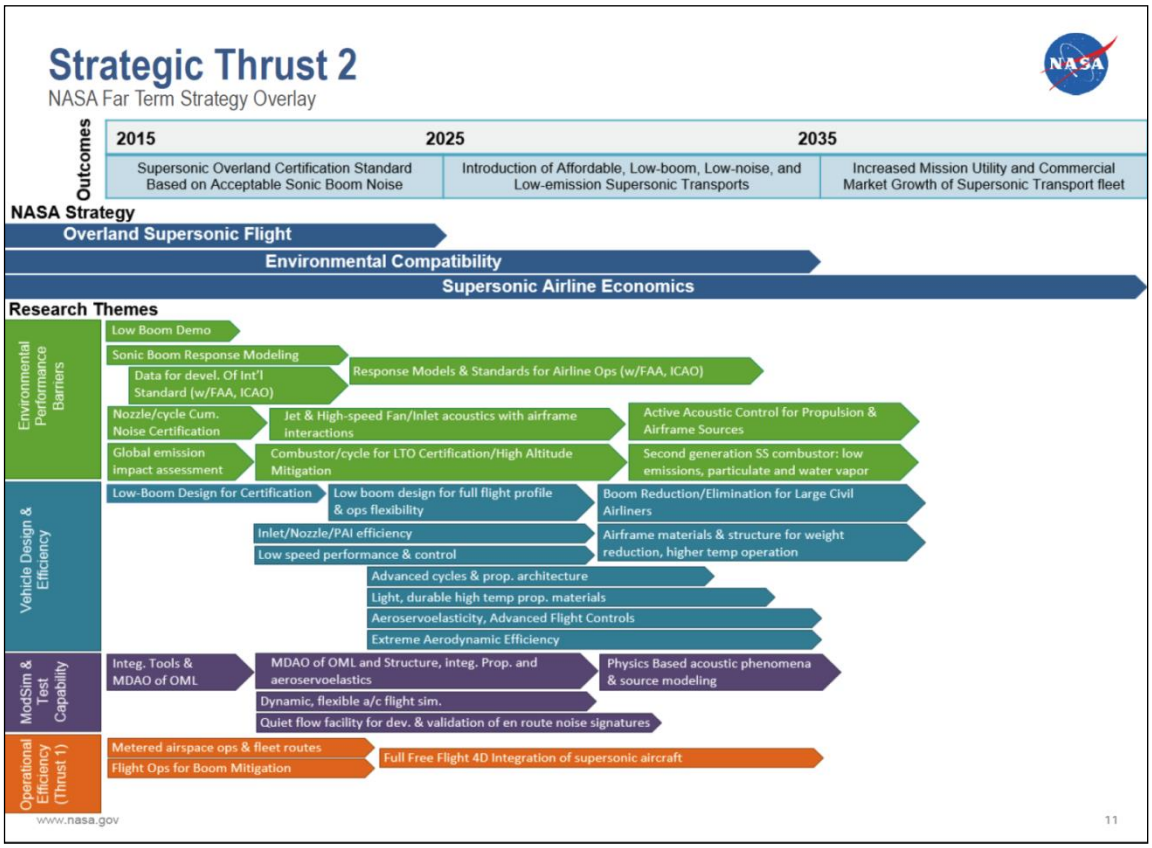


Figure 4.130: NASA Roadmap for supersonic activities [Coan P., 2016]

For the certification of emissions, the FAA suggests to apply Chapter 3. It should be noted that the NPRM for noise in combination with Chapter 3 for emissions would establish lower standards for novel SST aircraft both for noise and emissions respectively compared to the conventional civil subsonic aviation. Despite fundamental technical differences between supersonic and subsonic aeroplanes, and the comparative lack of maturity in civil supersonic technology, US manufacturers are fully committed to producing environmentally responsible supersonic aircraft and minimizing their environmental footprint.

Since 2016, the Japan Aerospace Exploration Agency has conducted research and development into future economically-viable and environmentally-friendly supersonic airliners through the System integration of Silent SuperSonic (SilentSupersonicTechnologyDemonstration - S3TD) program (Figure 4.129). The associated project aeroplane is a 50-seat,Chapter 14-compliant airliner with more than 3,500 nautical miles of range and a perceived sonic boom signature of less than 85 decibels. The agency has also developed sophisticated sonic boom modelling capabilities as part of its low-boom concept demonstration "Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom," and created a sonic boom prediction code called "XNoise," validated with measurement data from the demonstration.

As work continues on civil SST development programs and research initiatives, ICAO has a significant role in developing global environmental standards appropriate for future supersonic aeroplanes and engines.

Supersonic flights are usually at higher altitude, deep in the stratosphere, creating a larger impact on the atmosphere and climate compared to subsonic flights. Emissions from supersonic aircraft that would affect the atmospheric are oxides of nitrogen (NO_x) and water vapour. Main concern about the global environment is the potential for altering the composition of the atmosphere, particularly the ozone layer, which would affect the climate significantly. A set of exploratory studies was recently assigned to ICAO to develop understanding on supersonic aviation noise, emissions, and environmental modelling, with input from technical expert working groups. This work program is designed to assess environmental performance and demand scenarios for future supersonic aeroplanes and will afford a better understanding of the impacts of potential supersonic operations.

Since 2000 only very few EC funded projects were conducted in the area of supersonic aviation (Figure4.131):

- EPISTLE (DLR, ONERA): low speed aerodynamic performance prediction at take-off and landing of supersonic transport configurations.
- SOBER (Dassault, DLR): advanced numerical and experimental laboratory-scale simulation of sonic boom
- SCENIC (CU, DLR, ONERA): Emissions and climate impact of supersonic fleet
- HISAC (Dassault, ONERA, DLR): environmentally friendly high-speed aircraft design
- SUPERTRAC (ONERA, Dassault, DLR): laminar/turbulent transition prediction and control in supersonic flows
- RUMBLE (Dassault, DLR, ONERA): Modelling of the sonic boom itself and its effects on humans
- SENECA (DLR proposal to H-2020, 2020): (LTO) noiSe and EmissioNs of supErsoniC Aircraft

SCENIC is an EU-funded project focused on assessing the potential climate impacts caused by fleets of future supersonic aircraft. The project analyses a set of different emission scenarios over a range of fleet size, E.I. of NOx, cruising altitude, cruising speed, and range. The results confirm previous findings (IPPC, [Penner J., Lister D., Griggs D., Dokken D., McFarland M., 1999], Figure 4.132) that the emissions of water vapour in the stratosphere are the dominated factor to climate change. The simulation also predicts that a reduction in cruise altitude or speed (from Mach 2.0 to 1.6) helps to reduce ozone destruction and climate impact by approximate 40% [**GreweV.,** et al., 2007].

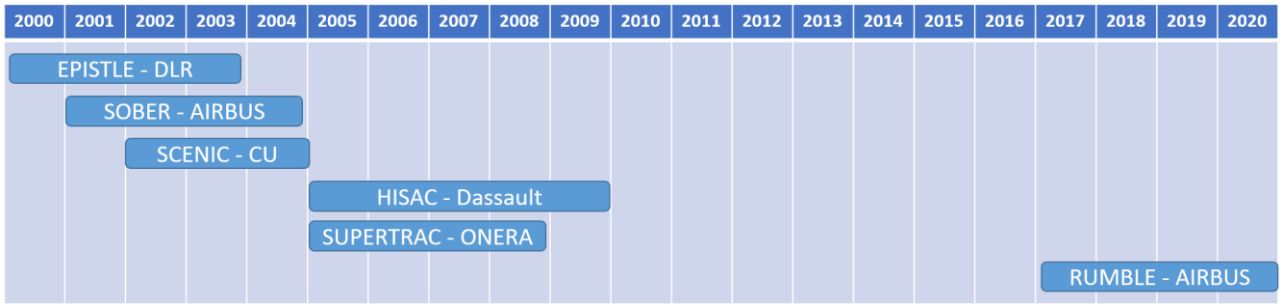


Figure 4.131: List of EC funded projects on civil supersonic aviation in the last 20 years [SENECA, 2020]

There have been other studies on the environmental impact of SST emissions, including the EU-funded HISAC project [Grewe V., et al., 2010, Grewe V., Stenke A., Plohr M., Korovkin V., 2010]. For aeroplanes cruising below the speed of Mach 2, it is concluded that an NOx index of 15 g NOx/kg_{fuel} appears satisfactory. From the National Research Council's study the water vapour emission index is referred to about 1400 g_{water}/kg_{fuel}. Most of European activities stem from the EC funded project HISAC [Pietremont N., Deremaux Y., 2005] - three classes of concepts (Figure 4.133) have been designed by different teams with the highest environmental objectives in terms of noise, emissions and sonic boom.

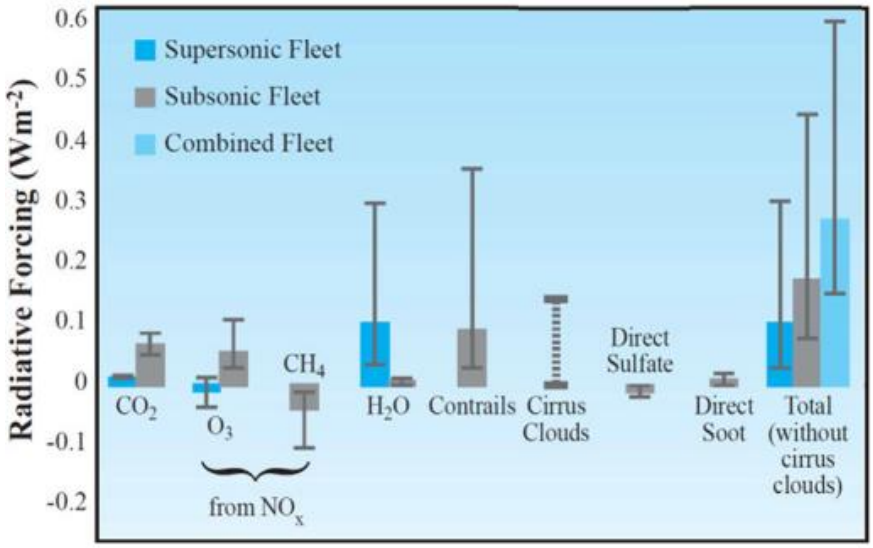


Figure 4.132: Radiative forcing from aircraft in 2050 with supersonic fleet [Penner J., Lister D., Griggs D., Dokken D., McFarland M., 1999]

Low drag and low boom are the biggest challenges for an SSBJ. These issues, however, are tightly related to many other aspects, such as wing configuration, body shape, propulsion system, structure, operations, and so on. Design methodologies that can properly predict the aerodynamic coefficients and sonic boom intensity are well worth exploring. Technological issues will be specified in this section and solutions will be addressed. The high-sweep wing, Figure 4.134a), is applied to the supersonic cruise aircraft primarily to reduce the wave drag. Another advantage of this configuration is that, during take-off and landing, at high angles of attack, the vortex produced by the leading edges can help to augment wing lift. The canard configuration, Figure 4.134b), compared with the aft tail configuration, exhibit of two advantages; lower trim drag and lower sonic boom intensity. The canard contributes to lift compared to a aft tail configuration. Hence the size of the main wing is reduced. The lower lift on the main wing leads to lower trim drag. The canard configuration can potentially mitigate sonic boom through a more uniform equivalent area and lift distribution along the length of the vehicle. Supersonic laminar flow is regarded as a key technology to improve the SST aerodynamic efficiency.

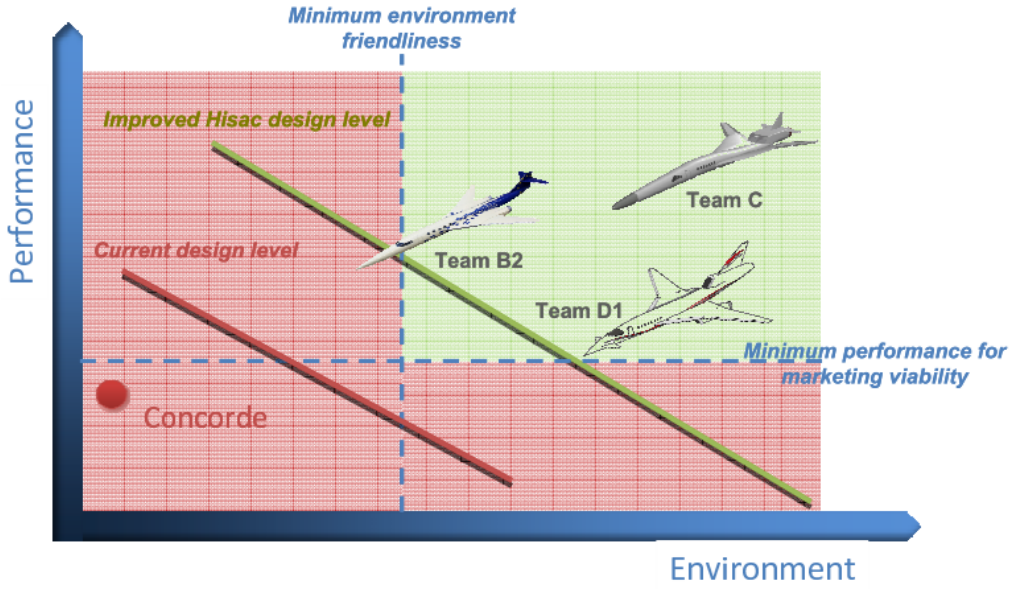
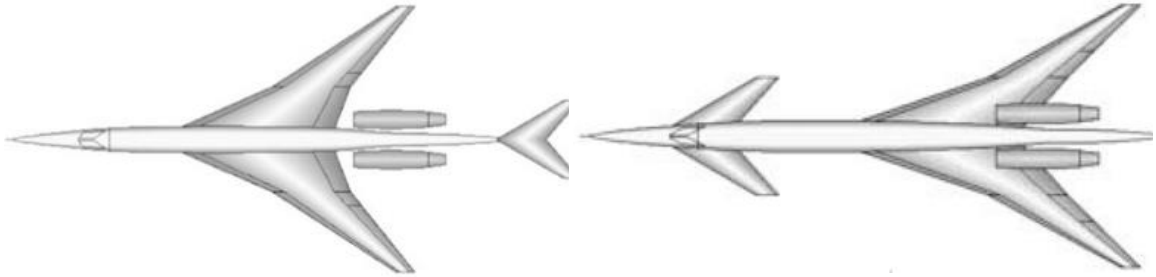


Figure 4.133: Three classes of concepts for SST 2.0 in EU projects during 2000...2020 [Pietremont N., Deremaux Y., 2005]



a) b)

Figure 4.134: Various configuration concepts for supersonic aircraft [Kroo I., 2005]: a) generic conventional SST wing configuration; b) generic canard SST wing configuration

Sonic boom signaturemitigation through aircraft shaping is based on the equivalent areaconcept established by Whitham [Whitham G., 1952] and Walkden [Walkden F., 1958]. To reduce theoverpressure for a given design, the equivalent area must be spread so as to increase the slenderness ratio as illustrated by the three sketchesshown in Figure 4.135. The sonic boom intensity is inverse proportion to theslenderness ratio ($\Delta p_{max} \propto d/L$). Thus the larger the L/d, the lower themaximum overpressure will be.

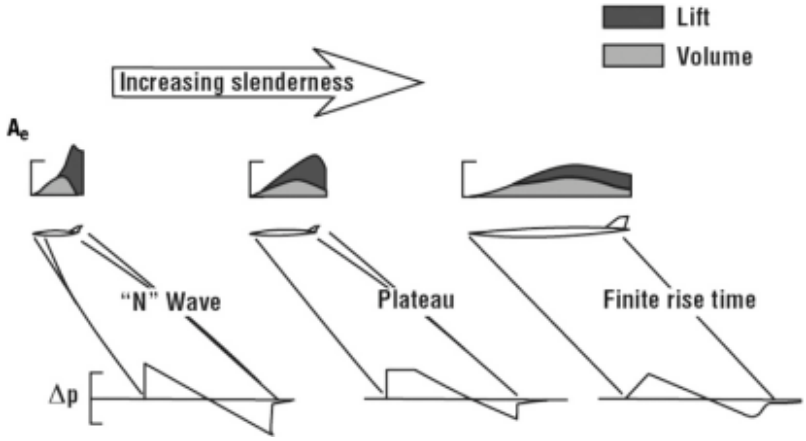


Figure 4.135: Relationship of signature shapes to vehicle area development [Maglieri D.J., et al., 2014]

Technical evidence shows that during the acceleration phases sonic boom levels will be of the same magnitude as those previously produced by Concorde in cruise. Such sonic boom levels led to the prohibition to fly at supersonic speeds over inhabited territories. As regards the cruise phase, the authors of this paper consider that perception of sonic booms in populated areas would constitute a new form of nuisance, whatever their intensity. According to the CAEP work program, assessment of sonic boom public acceptance is expected by 2025, since it requires a low boom demonstrator aeroplane [ICAO AN-Conf/13-WP/211, 2018].

For sonic boom the level of 65 dBA has been set as technical target for unrestricted operations. For community noise the SST 2.0 targets were considered as mid-term objectives for subsonic aircraft – ICAO Chapter 4 - 10dB. This new noise standard requirement is likely to apply to the future SST aircraft when operating in the subsonic speed regime to ensure some margin for operational flexibility and technological viability, this noise level of the SST will not be higher than current small business jets, as indicated in Figure 4.136. And for emissions during LTO operations (ground emissions), the targets are considered as ICAO mid-term objective for subsonic aircraft, for cruise emissions, an integrated approach combining aircraft + engine design and ways to operate it, allowed to optimize the emissions during cruise and to demonstrate the very low climate impact of a supersonic fleet. In terms of species quantification, the mid-term objective of EI_{NOx} has been revised to 10-12 g/kg fuel burnt.

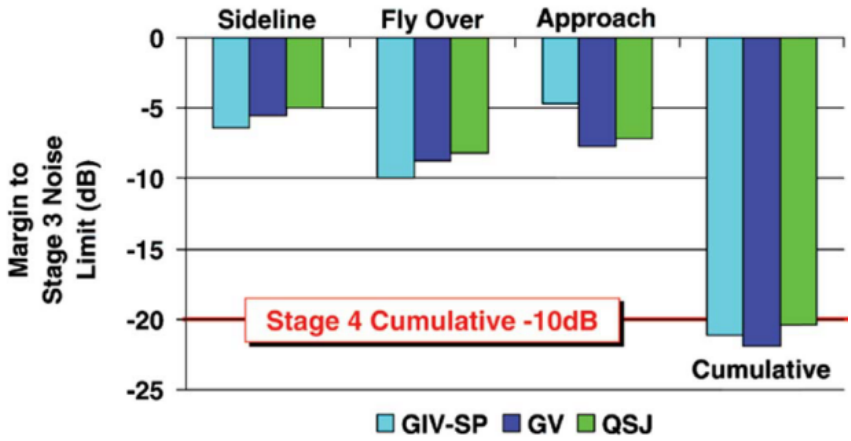


Figure 4.136: SSBJ community noise requirements (Source: [Henne P.A., 2005])

Promising technologies have been identified to reach these targets. Among them we can quote: variable confluence engine, innovative noise suppression systems, low boom technologies, challenging architectures and structures. Some of these technologies have links with subsonic aircraft ones (for ex. low NOx combustion chambers). Links with other relevant projects (concerning sub and supersonic aircraft) have been identified. In most of the cases the TRL of the specific technologies identified in HISAC is rather low.

In 2018, Austria presented a ICAO working paper [ICAO AN-Conf/13-WP/211, 2018] on behalf of the European Union, of all EU Member States, of other Member States, of the European Civil Aviation Conference, and of EUROCONTROL. The paper clearly states that less stringent noise limits would jeopardize the public acceptability of supersonic aircraft and that the emission regulations in Chapter 3 are outdated. The European position is to:

1) target the ***same*** noise limits for *supersonic* and *subsonic* aeroplanes;

2) revise Chapter 3 to provide an incentive to fit aeroplanes with best available environmental technology;

3) introduce carbon dioxide emission regulations, and

4) investigate the climate impact of the supersonic fleet especially with regard to the higher altitudes at which these aircraft would operate.

Figure 4.137 provides an illustrative example of how the noise footprint, in terms of area exposed to 80 dB sound exposure levels (SEL), of a typical 75-tonne maximum takeoff mass (MTOM) ICAO Chapter 3-compliant aircraft (blue) compares with an aircraft complying with Chapter 4 (green), and current Chapter 14 (red) noise limits. The area exposed to this level of aircraft noise by a typical Chapter 3 aircraft is twice that of a Chapter 4 aircraft, and more than three times as much area as a Chapter 14 compliant aircraft. Of those, 730 (57%) were single-aisle variants of the A320 family comparable in size to our reference SST (60 to 97 tonnes MTOM). The large majority (87%) of those certified variants are Chapter 4 aircraft (European Aviation Safety Administration, n.d.).

The authors of this paper [ICAO AN-Conf/13-WP/211, 2018] are of the opinion that internationally agreed environmental certification Standards are essential for the sustainable development of the aviation sector. Past development of subsonic noise standards has been effective at ensuring public acceptability of subsonic aircraft operations as one element contributing to the balanced approach to noise management. Therefore, the adoption of standards that would allow higher noise levels than subsonic aircraft does not guarantee the public acceptability of supersonic aeroplane projects in Europe. Such a situation would inevitably call into

question the purpose of ICAO Standards. Early evidence available indicates that supersonic aeroplane projects will not be able to meet current noise limits of subsonic aeroplanes due to criteria that designers have set themselves while detailed information on HISAC preliminary study indicate that it could be possible to design a supersonic aeroplane that meets maximum permitted noise levels for subsonic aeroplanes, even with conventional engines [ICAO AN-Conf/13-WP/211, 2018].

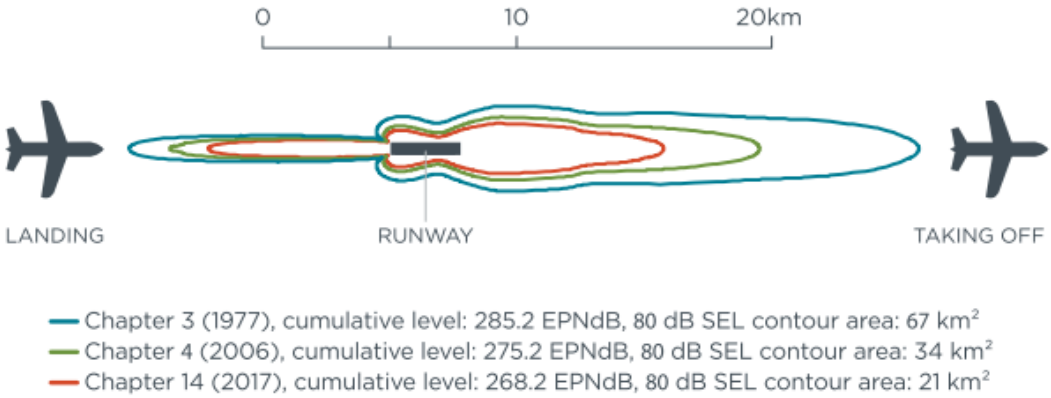


Figure 4.137: 80 dB Sound exposure level contours for 75-tonne aircraft just meeting the various ICAO chapter limits (adapted from EASA, EEA, and EUROCONTROL, 2016).

Currently, studies on LTO noise and emission are mainly carried out in the CAEP working groups described further. In one of these studies NASA worked together with Rolls-Royce on a Mach 1.6 - 81 tonnes Supersonic Transport Concept Airplane (STCA). The extension of this study will become a first input of SENECAproposal [SENECA, 2020] to CAEP 12, if the proposal will be adopted by EC. SENECA will also take into account results from HISAC. For instance, the business jet aircraft in SENECA will be based on the promising low noise configuration from HISAC (Figure 4.138) described further also.

EUROCONTROL, ONERA, NLR, and CIAM participated in the analysis of future noise constraints and concluded that progress in technology would seem realistic, and a new class for noise certification is likely to be created, with a new cumulative gain which is 10 dB less than in Chapter 4. Regarding future local noise constraints, a review of the current local noise constraints was performed. This overview of the practices of about one hundred airports, and their development over recent years, was used to establish a draft typology of airports based on the effective combination of elementary actions to cope with noise.



Figure 4.138: HISAC low LTO noise platform (Team A)

A noise level in the region of 87-88 EPNdB for a twin-engine S4TA (88.5 for a three-engine SST, 89.1 for a four-engine SST), which roughly corresponds to a level of 75 dBA in L_{Amax}, was expected on the ground as a limit in 2020, based on the evolution of European Directives. Due to the renewed interest of the US industry to develop and manufacture supersonic aircrafts with projects from different new entrants (Aerion Corporation, Boom Technology and Spike Aerospace) in the last few years, ICAO/CAEP has considered the need to develop a LTO noise standard for the noise certification of future supersonic aircraft.

In 2016, ICAO/CAEP/WG1 has created a specific Landing and Take-Off (LTO) noise subgroup to review the existing Annex 16 Vol I SARPs [ICAO Annex 16, 2019] and its associated environmental technical manual (ETM), developed for subsonic aircraft, and to identify their relevance to supersonic aircraft ("gap analysis") on the following topics : applicability, metrics, correlating parameter, procedures and limits. Several gaps have been identified which would need further investigation.

Those gaps were mainly due to differences in aircraft and engine design characteristics and performances between subsonic and supersonic aircraft:

- Supersonic aircraft need increased take-off speeds to ensure safe operations with a higher increment to V2 for the optimal L/D and climb gradients. This is due to specific design properties like lower wing aspect ratios, thin airfoils or high leading-edge sweep angles leading to a reduced maximum lift coefficient (CL_{max}).

- Supersonic aircraft have inherently excessive available thrust at take-off due to the engine design requirements for cruise or climb. A reduced thrust after lift-off would be needed to reduce the community noise levels and in particular the certified noise levels at the lateral condition. This is what is proposed by the Programmed Lapse Rate concept (PLR) with an automatic thrust variation performed by the engines by means of the FADEC.

The differences in low-speed aircraft performances motivated the definition of advanced take-off or landing procedures to mitigate the noise levels while ensuring safe operations representative of day-to-day operations.

Data provided by NASA or the US manufacturers has been used to support the gap analysis. NASA proposed a Mach 1.4 – 55 tonnes Supersonic Transport Concept Airplane (STCA), derived from a previous Boeing supersonic aircraft project, to estimate the noise levels without and with PLR, for two engine BPR (Bypass Ratio) and with chevrons as a jet noise reduction technology. As outcome, a 3.5 EPNdB cumulative margin vs. the chapter 4 limit with standard take-off procedures and a 4.6 EPNdB cumulative margin vs. the chapter 4 limit with advanced take-off procedures (use of PLR and accelerating climb-out) was estimated. Only the engine derivative comprising a BPR of 3.7 was able to comply with chapter 14 limits with standard take-off procedures (2.1 EPNdB cumulative margin) but with a penalty on the mission range of 3%. These results, published by NASA [Berton, J. J., Huff, D. L., Geiselhart, K., & Seidel, J., 2020], were confirmed by JAXA [Akatsuka, J., & Ishii, T., 2020].

Preliminary noise estimates for the project aircraft were in the same ballpark than the NASA STCA ones, leading the US manufacturers to call for less stringent noise limits than those of ICAO Chapter 14 [ICAO Annex 16,2019]for supersonic aircraft. This decision was mainly motivated by economical and risk mitigation considerations (re-using on-the-shelf engine technology as much as possible and design for reducing costs and uncertainties) as well as the need to account for usual development and test margins.

While FAA (US CAEP member) recommended that CAEP further develop a Standard and Recommended Practice (SARP) and conduct an associated stringency assessment for civil supersonic aircraft landing and take-off noise for consideration at CAEP/12 in 2022, the EU CAEP members, advised by their national experts, were asking for more robust data to address this "gap analysis". According to their views, chapter 14 limits are relevant for supersonic aircraft due to similar LTO operations than their subsonic jet

counterparts. They voted against less stringent limits as for subsonic aeroplanes, which would question progresses made during decades to reduce community noise and therefore finally the public acceptability of air transportation in Europe. Their views are technically supported by results from the HISAC study, where a LTO aircraft platform targeted to chapter 14 noise levels with margins was considered realistic, provided innovative technology developments.

As the requested robust data was not available to conclude the "gap analysis" and due to the different opinions among the different stakeholders, no agreement was found within the LTO noise subgroup. Consequently, within CAEP the elements of the certification will need further review.

The lack of consensus on the necessity to conduct a stringency option analysis on LTO noise for supersonic aircraft was noted at the CAEP/11 meeting in February 2019 and CAEP has decided to conduct an exploratory study using currently available data during the CAEP/12 cycle in order to provide CAEP with a better understanding of airport noise impacts resulting from the introduction of supersonic aircraft, and do not prejudge the need to conduct a stringency options analysis.

Aside the work undertaken by CAEP, the FAA Reauthorization Act of 2018 was issued by the US congress in October 2018 asking the FAA to develop a landing and take-off noise regulation for supersonic aircraft on a timeline that is within the CAEP/12 work programme.

The CAEP exploratory study (E-study) has started in 2019 (CAEP 12 cycle 2019-2022)with the following main activities:

- Recommendation of procedures for LTO noise certification;
- Development of multiple demand scenarios for supersonic transport markets;
- Development of environmental scenarios and data for the assessment of the impact on LTO noise, full-flight fuel burn and emissions on selected airports and flight routes.

Most of the CAEP working groups are involved (WG1 for noise, WG3 for emissions, MDG for modelling, FESG for forecast and economic analysis) and a specific Supersonic Coordination Group (SCG) was formed to facilitate the coordination and the exchange of data between the working groups.

Different aircraft platforms have been proposed by OEMs and NASA to support the E-study providing data related to the aircraft and engine performances, noise and emissions. On the EU side, Rolls-Royce has been working with NASA on a Mach 1.6 - 81 tonnes STCA. It has also been proposed to include the HISAC low LTO noise platform as another STCA. Due to the lack of required data for the E-study, the HISAC platform has been discarded from the demand scenarios and the whole airport impact assessments.

WG1 has recommended procedures for LTO noise certification, which have been agreed at the first CAEP/12 steering group in December 2019, provided they are only used within the E-study at this stage.

In line with the 2018 Reauthorization Act, the FAA has worked on a proposed regulation for landing and take-off noise certification of supersonic aircraft with a NPRM issued in March 2020.

The low LTO noise platform, proposed by Dassault Aviation (see Figure), had the specific objective of providing a cumulative margin of 10 EPNdB vs. the chapter 4 limit (equivalent to 3 EPNdB margin vs chapter 14 limit). Among the main characteristics of the aircraft were a targeted cruise Mach number of 1.6, a mission range of 4000 Nm, a 3 engines configuration (two located under the main wing and one mounted above the fuselage at the back) and a MTOW of 51 tonnes for a cabin size allowing 8 to 20 passengers.

European civil supersonic research on LTO noise and emissions has remained dormant since HISAC. SENECA will build on the results of HISAC and take also into account the latest studies from CAEP and extend

them[SENECA, 2020]. The ambition of SENECA is to take the next step to an environmentally friendly supersonic aviation. Therefore, SENECA will push technologies to a new level to ensure that supersonic aviation will maintain the existing high standards regarding noise applied to subsonic aircraft and make recommendations for new emission standards. The holistic approach of SENECA also includes the investigation of the climate impact of the supersonic fleet especially with regard to the higher altitudes at which these aircraft would operate. Achieving an environmentally friendly supersonic aviation with comparable standards to subsonic aviation is the minimum prerequisite for the public acceptability of civil supersonic aviation in Europe.

Fruitful discussion on the certification of supersonic aircraft can only be based on a comprehensive and reliable database. This database should show the impact of key aircraft and engine design parameters, of the landing and take-off trajectories, and of variable noise reduction systems (VNRS) on the certification levels. SENECA will deliver a very comprehensive database by investigating certification levels of supersonic aircraft across different platforms varying in payload and cruise speed for the first time. The reliability of the data will be enhanced by calculating the emission and noise levels of the different aircraft platforms with tools of different levels of fidelity ranging from empirical methods up to scale-resolving numerical simulation, redundantly by industrial and academic entities. This will allow the cross-checking of the results and hence will increase dramatically the credibility of the results [SENECA, 2020].

Innovative engine concepts and noise reduction technologies have been investigated during the HISAC project to mitigate LTO noise while relevant aircraft noise prediction models have been developed and used to assess the different engine and aircraft configurations. Two noise reduction technologies have been investigated in HISAC: a mixer-ejector concept and a conventional variable confluence (CVC) concept. Both concepts were aiming at reducing jet noise at take-off while minimizing detrimental impact on other performances of the engine or the aircraft (drag in cruise in particular)[SENECA, 2020].

Different mixer-ejector concepts were proposed by several partners (Volvo Aero/SENER, Snecma, Rolls-Royce, NLR, INASCO/ONERA and CIAM), Figure 4.139. The principle is to reduce jet noise by increasing the mass flow mixing with an external flow ingested in the nozzle through a dedicated scoop, upstream of the lobed mixer. Different acoustic treatment solutions were proposed by INASCO and ONERA to mitigate the high frequency noise due to the lobed mixer. The most promising mixer-ejector concepts were manufactured at model scale for a test campaign at the ONERA Cepra19 anechoic wind tunnel facility which confirmed a noise benefit of 6-7 EPNdB at source between the best mixer-ejector concept and a reference confluent nozzle.

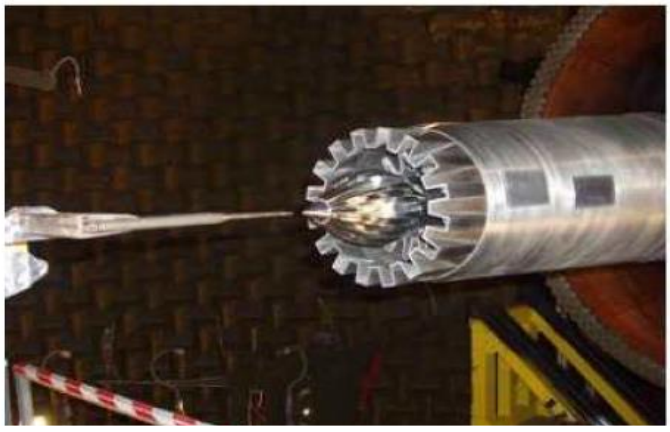


Figure 4.139: Example of a mixer-ejector concept tested at the ONERA Cepra19 wind tunnel

A CVC concept was investigated by Rolls-Royce and the Polish Institute of Aviation, who proposed an axially translating mixer concept, Figure 4.140. The principle is to reduce the primary core jet velocity at take-off and so jet noise by increasing the core duct and the nozzle exit areas while reducing the bypass duct area at the

mixer plane. This provides a higher bypass ratio (BPR) while keeping the propulsion system wet surface small to prevent excessive drag in cruise. The mechanical integration was studied by SENER.

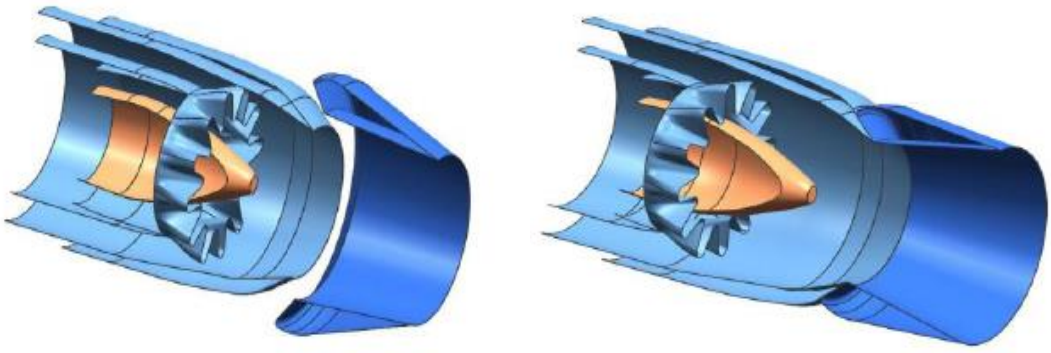


Figure 4.140: CVC concept with an axially translating mixer (left: TO configuration, right: cruise configuration)

Dedicated engine noise sources models have been developed in HISAC, relevant to supersonic engines operating in LTO flight conditions. ISVR has developed a semi-empirical jet noise model based upon a breakdown between the external and the internal jets with a dedicated model for each individual jet noise source. This jet noise model was successfully validated against the measurements made at Cepra19 during the mixer-ejector noise tests (Figure).

Dassault Aviation, Alenia Aerospace and NLR have performed aircraft noise estimates on a benchmark configuration consisting of a reference shape and two conventional engines of BPR 3.5 mounted above the fuselage (Figure). While all estimated noise levels were lower than the ICAO Chapter 4 limits, there were discrepancies in the predictions due to different assumptions: no shielding was accounted for by ALENIA and NLR, no airframe noise contribution was taken into account by Dassault Aviation. The most critical condition was confirmed as the lateral one, for which the engine is at the maximum thrust and jet velocities and therefore noise levels are the highest, with small margins vs the ICAO Chapter 4 lateral noise limit.

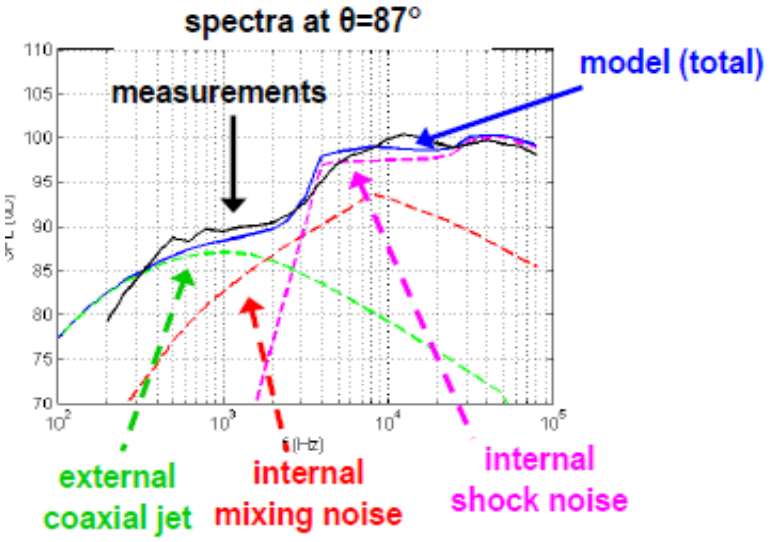


Figure 4.141: Results of the jet noise model developed in HISAC by ISVR and comparison with Cepra19 noise measurements

Advanced take-off procedures were investigated by CIAM, who concluded that only joint optimization of aircraft and engine design variables and thrust management may give maximum benefit on range with noise requirements satisfaction.

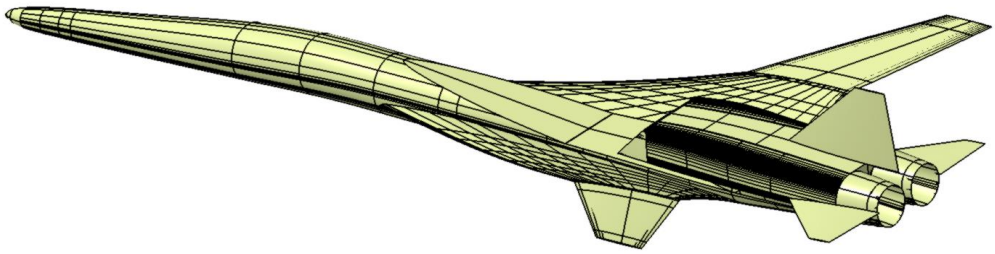


Figure 4.142: HISAC reference aircraft shape for the evaluation of LTO noise levels

In NASA a notional 55 tonne supersonic technology concept aeroplane was discussed in a [Berton, J. J., Huff, D. L., Geiselhart, K., & Seidel, J., 2020], it has been developed and studied at the request of the FAA and ICAO. The influence that supersonic aeroplanes will have on operations, fuel consumption, airport noise, and air quality is being assessed by a CAEP exploratory study, with the NASA 55t STCA serving as an analytical proxy for similar early market entrant supersonic aeroplane types. Being nonproprietary and transparent, the 55t trijet is ideal for use in ICAO's public studies. Aircraft performance, airport-vicinity noise and exhaust emissions are predicted using NASA tools. Using an advanced takeoff procedure, the 55t STCA is predicted to have a Chapter 4 cumulative noise margin of 1.6 EPNdB. Range for a maximum takeoff gross weight mission is 4243nmi. Characteristic exhaust emissions are predicted. Also investigated are some of the anticipated behaviors and requirements of these aircraft in the terminal airspace, the influence of alternative engines, and a lighter, 45t supersonic twinjet.

Two thousand commercial SSTs would emit an estimated 96 Mt of CO_2 per year in 2035 (88 Mt CO_2 to 114 Mt CO_2 for best and worst configurations, respectively). Compare that with the 162 Mt CO_2 emitted by US airlines in 2017. Under the "higher impact" induced demand scenario, all of these emissions would be in addition to the emissions from the existing subsonic fleet; under the "lower impact" scenario, which assumes complete substitution from subsonic business class, SSTs would add 64 Mt CO_2 (59 to 76 Mt CO_2) to the existing subsonic inventory[Rutherford D., Brandon G., Chen Chen, 2019].

The small-size SSBJ has been consistently regarded as the pioneer of the next-generation supersonic civil transport [Sun Y., Smith H., 2017]. The steady growth in air traffic calls for more efficient, faster commercial transport. Several studies lead to a convincing high-end market in business class transport. Regulations appropriate to supersonic airliners need to be introduced in the near future as the studies on sonic boom acceptance continue. The need to reduce the sonic boom loudness and supersonic cruise drag are of vital importance. There seems to be a common view on the mission specifications of the SSBJ. With the trans-Atlantic ability, the number of passengers between 8 and 12, and a cruise Mach number of about 1.8, the SSBJs are highly constrained by environmental concerns. However, it is not easy to balance these concerns with the 'value of time' benefits offered by the high speeds. The low-boom requirement restricts all aspects of the design from wing shape and fuselage geometry, cabin and nacelle, through to aerodynamic performance, engine selection and propulsion integration to the applications of other novel technologies. Public acceptance plays an important role in the return of supersonic transport. A possible approach is the development of a flight demonstrator scaled to produce a representative reduced boom waveform signature and assess the response of the public.

The analysis [Rutherford D., Brandon G., Chen Chen, 2019] highlights the need for robust environmental standards to manage the expected noise and CO_2 impacts of reintroducing commercial SSTs. As for CO_2 emissions, since ICAO adopted a global Standard limiting emissions of subsonic jet aeroplanes, it seems to be essential to also subject supersonic aeroplanes to a standard, particularly as this new class of aircraft will

have significantly increased fuel burn and therefore CO_2 emissions on both a per aircraft and per passenger basis, compared to existing aircraft. The absence of a Standard would place supersonic aeroplanes in a situation of unfair competition [ICAO AN-Conf/13-WP/211, 2018]. The full climate impact of supersonic air transport is likely to be different to subsonic aircraft, due to the higher altitudes at which these aircraft would operate. This includes impacts of particulates and NO_x on stratospheric ozone depletion and ultraviolet radiation. The science of these effects is not well understood but represents an additional climate impact compared to subsonic aircraft.

The estimated 5000 SST flights per day in 2035 could lead to more than 100 Chapter 3 noise flights being introduced at each of eight airports globally[Rutherford D., Brandon G., Chen Chen, 2019]. Large regions of the globe could be exposed to sonic booms at a frequency of more than once per hour. Increasing CO_2 emissions from these aircraft could make it even more challenging for industry to achieve its climate goals. International standards will be needed given that 87% of projected flights would depart one country and land in another. ICAO is initiating work on SST standards for LTO noise, air pollution, sonic boom, and cruise CO_2. A full set of standards may be finalized by 2025 and take effect before 2030. Regulators are faced with two choices: either to develop new SST standards that would allow those aircraft to produce more noise, air pollution, and climate pollution than new subsonic designs, or to apply existing subsonic standards to SSTs. Aspiring SST manufacturers could boost public acceptance for their designs by committing to meet existing LTO noise and cruise CO_2 standards for subsonic aircraft and by supporting new en route noise standards that would mandate low-boom technology. Lacking these commitments, manufacturers may find it difficult to access additional capital to finalize their aircraft designs: to date, Boom has raised about $141 million, or about 2% of the $6 billion it estimates will be needed to fully develop its aircraft [Rutherford D., Brandon G., Chen Chen, 2019].

Despite these challenges, considerable investment has been made in de-risking many of the enabling technologies and raising readiness levels [Sun Y., Smith H., 2017]. Many technologies are moving beyond theoretical and numerical analysis into the experimental and flight testing domains. The multi-disciplinary design, analysis and optimization with higher-fidelity capacities can hopefully carry out in-depth studies founded on physics to limit the design space and thus to reduce future development costs. The efforts from both the industry and the academy will speed up the process in bringing commercial supersonic aircraft back. The next-generation low-boom supersonic flight is expected in the next few years.

The environmental impact of civil supersonic aeroplane projects remains a major concern. The adoption of certification standards that would allow higher noise levels than those for current and future subsonic aeroplanes does not guarantee the public acceptability of supersonic aeroplane projects in Europe. The authors of the paper [ICAO AN-Conf/13-WP/211, 2018] consider that the environmental impact must be addressed holistically for noise and emissions before considering the introduction of supersonic aeroplane projects into the global air navigation system.

4.1.8. Drones and urban air mobility

As populations in megacities continue to grow, the increased urbanization and traffic situation is pushing ground transport systems to their limits. Bringing urban mobility to the third dimension offers the potential to create a faster, cleaner, safer, and more integrated transportation system. Urban Air Mobility (UAM) refers to a range of vehicle concepts and missions operating in a community, from small Unmanned Aerial Systems (sUAS) to vehicles large enough for several passengers. The sUAS are envisioned for package delivery, surveillance, agriculture, surveying, and other similar applications that can benefit from use of a small and agile autonomous system, while the larger vehicles are envisioned for on-demand urban passenger transportation. Electric propulsion is seen as a key technology that could enable these kinds of systems, across the range of vehicle types and sizes.

A new mode of inter-modality will impact on understanding the needs and concerns of the population from urban areas and nearby communities on UAM deployment. This activity is also linked to impacts on public authority and standardization. If successful, the methods may contribute to the **design and development of an acceptable path for integrated mobility** in smart and sustainable cities**.** The embracement of mostly electric or hybrid UAM will contribute to **low carbon and resilient cites,** in line with EU policies, conducting in different tasks dedicated to energy and environmental impact. New aircraft technologies for increased mobility are likely to lead to new sources of community noise.

Autonomous aerial vehicles and flying cars are no longer science-fiction: projects and trials are already taking place around the world. Major aviation and automotive manufacturers, city authorities and technology companies are working on innovative urban mobility solutions.

Mobility is a determining factor for the quality of life in urban areas. The expected doubling of the urban passenger mobility demand by 2050 will push conventional ground based transportation to their limits. Moreover, their enhancement is limited due to large investments, footprints, and lead-times required. Metropolitan areas and cities will consequently face significant challenges with regards to ***pollution, noise,*** and ***congestion***.

A number of transportation services has been successfully used for safe and time-efficient long-haul transportation for decades. Already today, conventional helicopters operate as air taxis in cities like New York City, Figure 4.142. An 8-minute flight from JFK Airport to Lower Manhattan costs around $200 USD per passenger using the *Uber*Copter Air Taxi Service. Also, Blade offers an Airport Pass for an annual fee of $295 USD, with which each flight between Manhattan and NYC airport costing $145 USD. Comparing this with ground transportation, the same trip costs $55 USD for a regular taxi and $120 to $180 USD for a more comfortable Uber Black Service, but takes 55 to 100 minutes.



Figure 4.143: Comparison between conventional ground based (red line) and air transportation (white dashed line) for connection Manhattan and JFL airport in New-York city

As urbanization, population explosions, and the growth of mega-cities continues, governments and private companies must address infrastructure challenges. After a world-first first test flight of an air taxi in an urban environment in Singapore at the end of October 2019 [https://www.straitstimes.com/singapore/flying-taxi-goes-for-test-spin-in-marina-bay], there has been much excitement surrounding the future of the fledgling UAM industry. UAM is a concept for air transportation around metropolitan areas consisting of passenger-carrying operations. An emerging UAM market will require a high density of vertical takeoff and landing (VTOL) operations for on-demand, affordable, quiet, and fast transportation in a scalable and conveniently-accessible "vertiport" network. It is envisioned that UAM will provide increased mobility within a given metropolitan area by flying faster and using shorter and more direct routing as compared to ground vehicles (Figure 4.144).

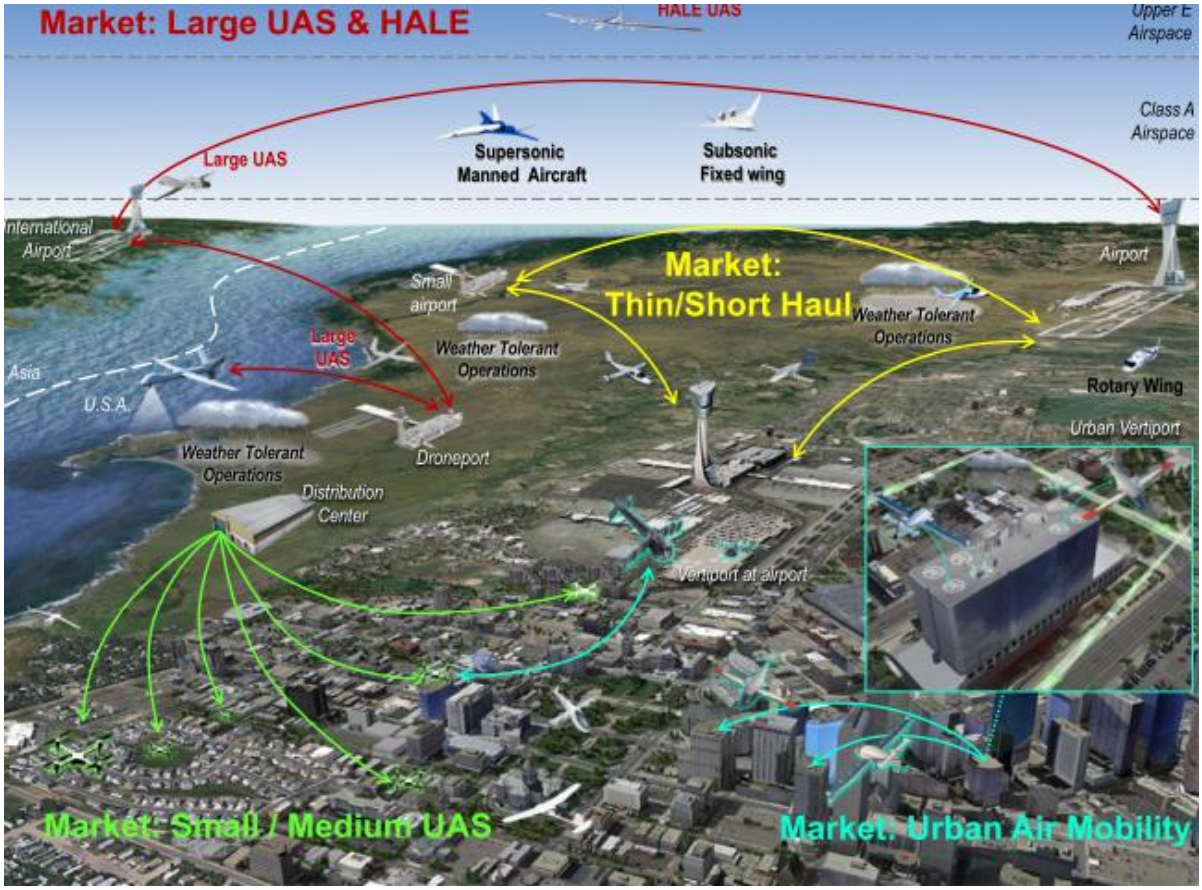


Figure 4.144: Integrated Aviation System architecture framework

Air Taxi market generates ~98% of its demand by capturing part of the long trips (i.e. 30 mins and more) served by ground transportation (Figure 4.145, [UAM Market Study, 2018]). Many city administrators have put Smart City policies at the centre of their plans, with UAM as a core component (Figure 4.146). While the timescale for full deployment is uncertain and many obstacles still lie in wait from a regulatory and legal perspective, UAM and vertical take-off and landing air vehicles (VTOLs) undoubtedly have a part to play in the future development of urban environments. VTOLs offer a potential solution to the issue of urban congestion; they minimize the need for a runaway and, in many cases, reduce the need for other modes of transportation to move passengers from those runways to their final destination. VTOLs also offer more direct point-to-point transportation and, undoubtedly, their most compelling use cases are for urban air taxis and final-mile cargo deliveries. As with any new technology, there are many unresolved issues with UAM posing legal and regulatory challenges that touch on most aspects of aviation, especially the areas of air traffic control/management as well as flight standards and certification. Other areas of concern also include environmental policy (noise and emissions), public use, land use (i.e. for vertiports/terminals), and liability/insurance arrangements. Environmental factors such as noise and visual annoyance from air vehicles to perceptions about privacy and a sense of trust in these new systems are all very important to plan for accordingly.

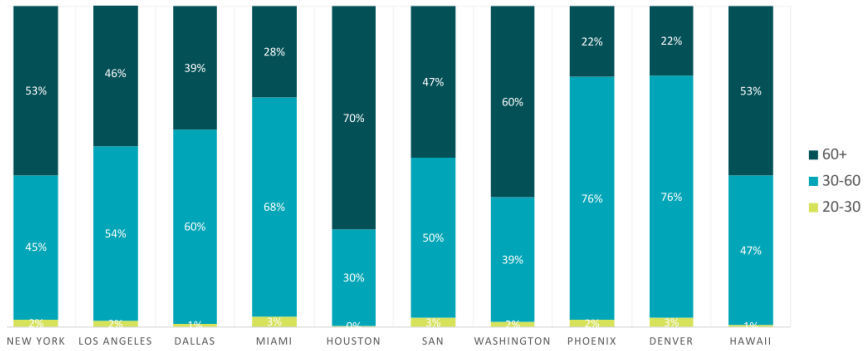


Figure 4.145: Percent of UAM trips captured for ten focus urban areas [UAM Market Study, 2018]

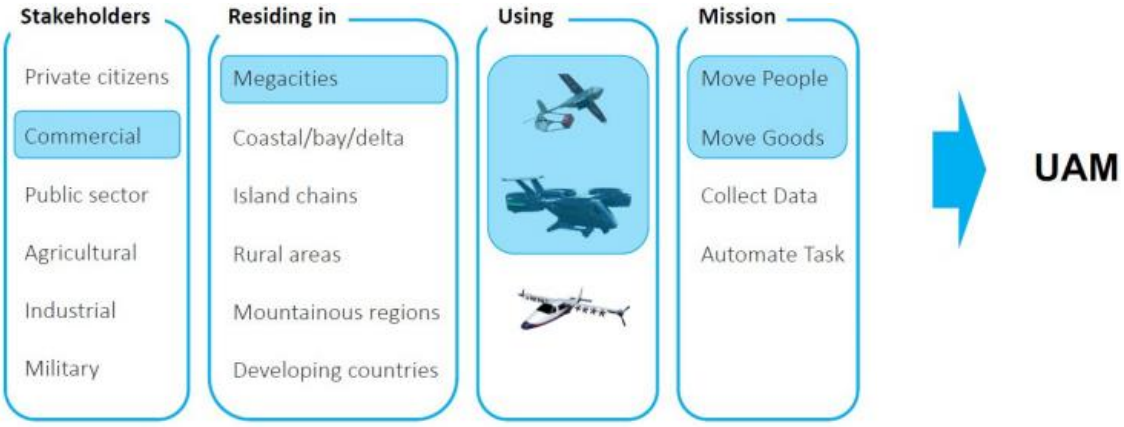


Figure 4.146: Advanced aerial mobility covers a diverse set of stakeholders, deployment environments and use cases, not limited to urban air mobility [Advancing Aerial Mobility, 2020]

Success of advanced UAM will be dependent on several factors if they are to be accepted from an economic, social, and regulatory standpoint. Some of these factors are [Advancing Aerial Mobility, 2020]:

Safety: Advanced aerial mobility will have to demonstrate the high safety levels expected by the public for modern air transportation systems.

Security: Emerging technologies present new cybersecurity risks and vulnerabilities that will have to be managed.

- *Social acceptance*: New products or services applying advanced aerial mobility must gain the trust and support of the public, taking into account multiple factors.
- *Resilience*: Contingency management, the ability to manage the expected and the capability to recover from the unexpected will be a key to success.
- *Environmental impacts*: Factors such as noise and visual impact from air vehicles on the environment and nonparticipants, as well as greenhouse gas emissions and any associated air pollutant emissions, will have to be minimized to acceptable levels.
- *Regulation*: New rules to accommodate the technology as well as to define its integration into the National Airspace System will have to be created.
- *Scalability*: Any successful approach to advanced aerial mobility will need the capability to scale as the market segments emerge and grow.
- *Flexibility*: With any disruptive new initiative, flexibility is critical as new use cases and operational concepts emerge.

Architectural decisions for new UAM include specifications sufficient for future standards and implementation development (Figure 4.147) in areas such as the following:

- System architecture framework—defining the principal elements, functions, and interfaces of the system;
- Communications—assumed communications capabilities, including decisions for spectrum, data exchange, and cybersecurity standards;
- Approaches to adapting architectural function and components over time; and
- Evolution of existing safety evaluation approaches.

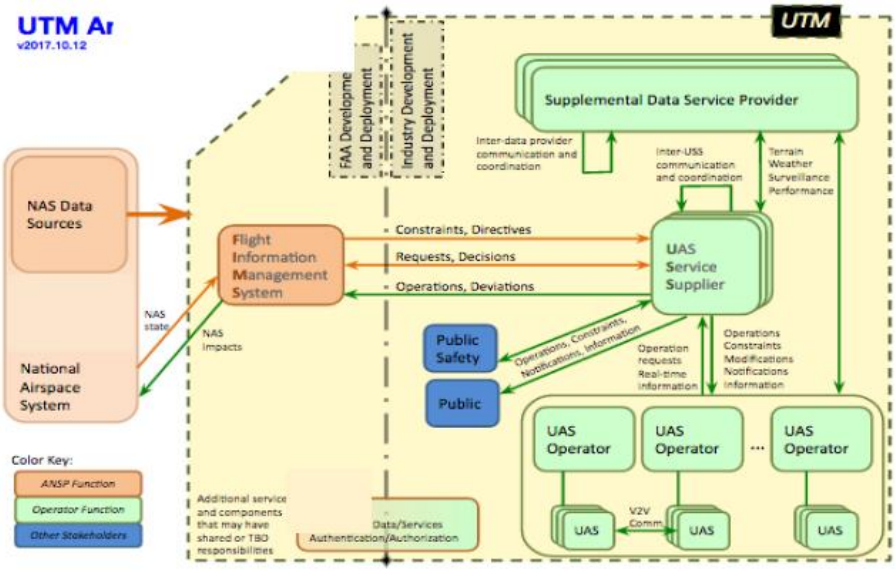


Figure 4.147: UAS Traffic Management Architecture – 5G Connections & communications are internet-based & built on industry standards & protocols [UAM Market Study, 2018]

A key application area for new capabilities in flight is UAM, air passenger and cargo transportation within or to/from a metropolitan areas with vehicles ranging from small drones to passenger aircraft, including in some cases electrically powered vertical takeoff and landing (eVTOL) capabilities. Four general areas need to be addressed [Advancing Aerial Mobility, 2020]:

- *Technology*: Technological advances will be needed to scale what exists today. These advances include acoustics and noise reduction, autonomy and software capabilities, ways to design safety into the system and to convince the users that risk is acceptable, and efficiency to overcome cost barriers.
- *Operations*: The public will not accept greatly increased flight operations over their homes and in their "airspace" unless noise and obtrusiveness, and the resultant effects on family and community life, can be minimized. Safe interoperability with all other aircraft in both controlled and uncontrolled airspace classes must be assured.
- *Safety and privacy*: The success of traditional transport systems has hinged on the ability of the industry to convince the public about its safety. Whether or not the fears are rational, success of advanced aerial mobility will require a very high safety record. The potential impact of advanced aerial mobility on privacy and security will need to be at publicly acceptable levels.
- *Public relations*: A public relations campaign will be necessary to overcome any natural fears or misunderstandings and to build trust in these new systems. This campaign will have to include purposeful public messaging, education, and case studies and demonstrations of benefits. Enlisting the public as stakeholders and advisors can also be effective. Part of the messaging and case studies will likely be services provided by other parts of advanced aerial mobility that will have the greatest

impact and attraction by the public, such as first responders, disaster relief, crime reduction, and firefighting.

Concerning eVTOL - electrification of transport combines an energy efficient power train system with the opportunity of using any source of energy other than fossil fuels including those from renewable sources. Transport sector electrification is essential for meeting the European Union goals of decarbonization and energy security, as it accounts for 25% of all CO_2 emissions in Europe [Electrification of the Transport System, 2017]. The electrification of transport requires the integration of vehicles into a reliable and affordable as well as easy-of-use infrastructure for the supply of energy. In aeronautics, electrification will not go beyond very small and short range small aircraft or operations on the ground for the next decades.

Commercial aviation has been a 40-year growth market and that there is little sign that the relationship between GDP and market growth is weakening, thus predicting that it should remain a healthy growth market on which new players try to capitalize. Cycles do come and go in a market, but when it comes to aviation, the cycles are occurring on a trend of net growth.

John Hansman, a Professor of Aeronautics & Astronautics of the Massachusetts Institute for Technology, introduced at visioning workshop Aeronautics 2050 [Aeronautics 2050, 2018] the theme of challenges and opportunities for today's commercial aviation sector. He started by reviewing 11 of what he believes are the greatest challenges (and opportunities) facing the industry today (selected text in italics is connected with UAM implementation greatly): (1) international growth trends in traditional aviation markets, with emphasis on growth potential in Asia; (2) ***growth in emerging nontraditional markets, such as unmanned aerial vehicles (UAV), urban air mobility, and commercial space launches—he noted that there are now over 940,000 registered UAV operators in the United States***; (3) stimulating innovation in high-integrity markets in which innovation leads to financial loss; (4) engendering excitement in and meeting the expectations of the young workforce; (5) ***modernizing the national civil aviation system while maintaining safety—the current high level of safety can lead to conservatism, but how much do you want to spend to mitigate a concern that is a very low risk***; (6) ***emerging nontraditional safety threats, such as the proficiency of human interactions with increasingly automated systems that require nontraditional training***; (7) the emerging shortfall of pilots and technicians; (8) the capacity of the national airspace system (NAS), in particular capacity around markets such as New York City and runway capacity at key locations; (9) ***low-altitude urban airspace capacity with the inclusion of MedEvac and Uber-type transport ideas;*** (10) ***low success in implementation of modernization, partly because of the high level of safety in the current system***; and (11) ***environmental issues, including greenhouse gas emission, noise pollution, and ultrafine particles***.

An UAV or drone industry has come a long way in the last five years. Numerous innovative drone manufacturers and applications have emerged around the globe, and according to the US FAA, there are now over 1.5 million drones registered in the U.S. alone. The industry has designed, tested and launched the fundamental technologies for UAS Traffic Management (UTM). The drone industry is now ready to scale in a big way. So get excited about drones becoming part of your daily life, and be on the lookout for these five major developments I predict we'll see in the 2020s [Marcus B., 2020].

Air Taxi market has a potential demand of ~55k daily trips (or ~ 80k daily passengers) across the US that can be served by ~4k aircraft. Based on near term market entry assumptions, annual market value is projected to be ~$2.5 billion for the first few years of operation. For the first few years of operation, market value of total available demand is projected to be ~$500 bn while only ~$2.5 bn can be potentially captured due to operation constraints [UAM MARKET STUDY, 2018].

PwC (PricewaterhouseCoopers–a multinational professional services network of firms mostly concentrated on audit and consulting) estimates in [Communications Review, 2017] that the total addressable market for commercial drones is $127.3 billion. That includes $45.2 billion in infrastructure, $32.4 billion in agriculture,

$13 billion in transport and $10.5 billion in security. As more corporations look to capitalize on these commercial opportunities, investment continues to grow. According to Drone Industry Insights' [Drone Market Report 2019], energy is the largest industry participating drone market, but transportation and warehousing use of drones is growing fast. The big picture, the most important figure to take away, is certainly 43 billion USD. That's how big the drone market will grow to be in 2024. Having generated 14.1 billion USD in 2018 it will grow at a CAGR (Compound Annual Growth Rate) of 20.5% to almost triple that in 2024. As seen in Figure 4.148, this strong growth is also a reflection of the ongoing high investments and the consolidation of the commercial drone market.

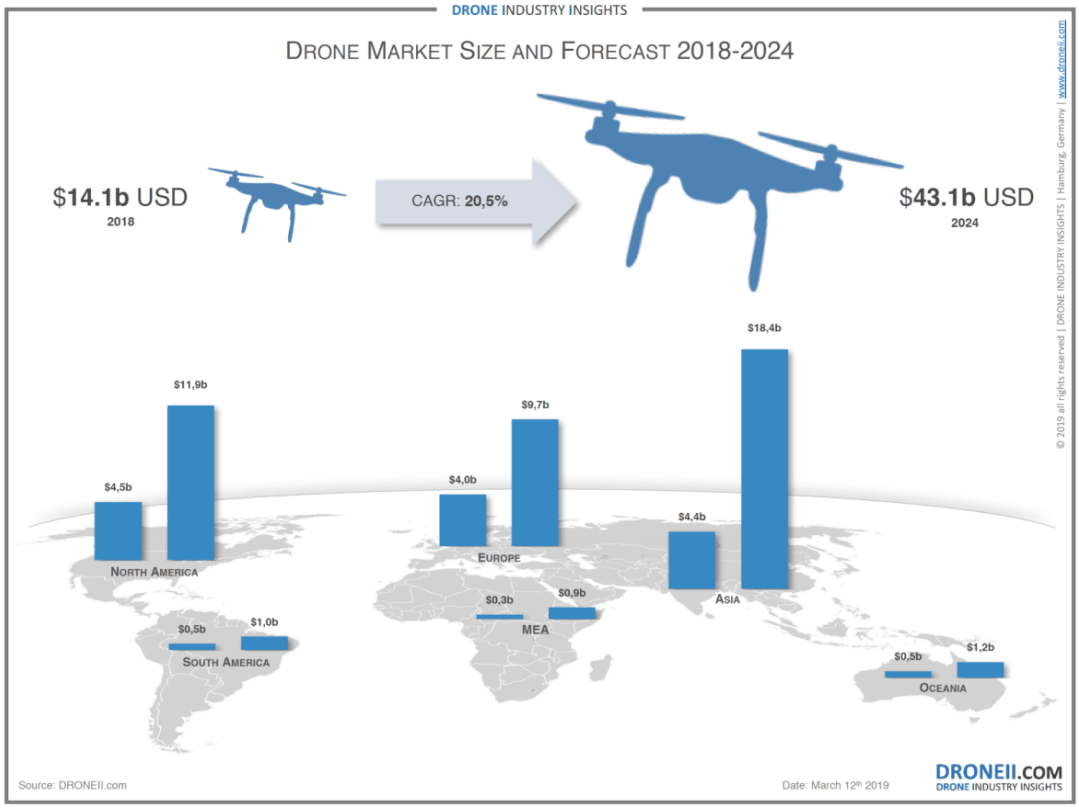


Figure 4.148: Global drone market size and forecast 2018-2024 [https://www.droneii.com/the-drone-market-2019-2024-5-things-you-need-to-know]

The energy sector was the largest industry in 2018 and will continue to be so in 2024. However, the Transportation & Warehousing industry will continue to be the fastest growing. This is partly because, as defined by the North American Industry Classification System this vertical includes industries providing transportation of passengers (although air taxis won't sell for some time still) and cargo, warehousing and storage for goods, and support activities related to modes of transportation like inspection and maintenance of infrastructure. While agriculture and construction currently follow energy as the top industries in the drone market, the growth of the transport sector will mean that in 2024 transport will be the 2nd largest industry on the market.

The US and China currently dominate the commercial drone market – together their revenue makes up over 2/3 of the global drone market. While North America in 2018 generated slightly more revenue than Asia, thanks to the growth of not only China, but also Japan and especially India, Asia will majorly pull ahead already by the end of 2019. Having legalized drones at the end of 2018, India has already been a rapidly evolving market. By 2021, the commercial drone industry will have sold 1,000,000 units. Looking at the growth between 2018 and 2024, unit sales will have tripled in this time period.

US NASA has announced plans for a Grand Challenge series aimed at providing a proving ground where NASA, vehicle providers, airspace technology providers, and the public learn what it really requires to achieve UAM and operate air vehicles safely in an urban environment [nasa.gov/uamgc]. In late 2020, there will be developmental testing to prepare for an initial Grand Challenge in 2022 involving a small set of participants, followed by the full Grand Challenge involving many more participants.

The Grand Challenge itself will be a full field demonstration in an urban environment that tests the readiness of companies' vehicles and airspace operators' systems to operate during a full range of passenger transport and cargo delivery scenarios under a variety of weather and traffic conditions.

The objectives of the challenge are to:

- Accelerate technology certification and approval
- Develop flight procedure guidelines
- Evaluate communication, navigation and surveillance options
- Demonstrate an airspace system architecture based on NASA's Unmanned aircraft systems Traffic Management (UTM) construct
- Collect initial assessments of passenger and community perspectives on vehicle ground noise, cabin noise and on-board ride quality

According to NASA, the timeline for the Grand Challenge series is dictated by when participants will have technologies ready to test including vehicles (passenger-carrying, cargo-carrying/delivery, sensing/detecting) and the systems required for successful communications and navigation. By the end of the decade, NASA estimates that there will be approximately 23000 air taxis transporting around 740 million passengers worldwide. With UAM, we can reduce fossil fuel emissions and open the door to using airspace to provide emergency services to people in crisis.

Operating small combustion-powered aircraft proved to be too expensive, and their complexity and consequent maintenance made them costly and unreliable. At the same time, piloting aircraft remained complex, with steep training requirements that held back growth in the pilot population. These forces limited scale and innovation and combined to keep aviation for personal transport beyond the reach of mass adoption. Ultimately, 20th century technology was not able to support a product that could scale into the needs of the personal aviation market. (Figure 4.149). In contrast, commercial aviation thrived. Here, efficiencies could be gained through larger aircraft and complexity managed with highly trained professional pilots. Early regulated air service transitioned through deregulation and route structure and business model innovation. Today, as tens of thousands of people pass through mega-hub airports daily, one might wonder if personal aviation was a misguided idea or just before its time [Advancing Aerial Mobility, 2020].

The only way to unlock these benefits at scale is with a robust, safety-first and automated air traffic management system designed for autonomous aerial vehicles. The UTM system we're building today will serve as the bedrock for UAM. By creating a new air traffic management paradigm that allows drones to fly safely, autonomously and at scale, we pave the way for a future where Jetsons-style flying taxis will be the new normal.

Setting up a suitable UAM infrastructure is a major challenge for any city. Due to its nature of picking up passengers or dropping them off in closely congested city districts, "vertiports" must be integrated into an existing city infrastructure and architecture, ensuring a fast but also secure boarding and deboarding. For a seamless journey, the vertiports need to be linked to other mobility solutions such as metro or first- & last-mile transportation. In addition, the vertiport design must be developed in close alignment to the aircraft as various aspects are impacted, e.g. landing platform dimensions or operational requirements such as charging equipment.



Figure 4.149: Factors in both the aircraft fleet and pilot population inhibited general aviation's progress and scale [Advancing Aerial Mobility, 2020]

Airbus predicts that, by 2030, the UAM market will be worth an accumulated $50 billion, less than half of which will go to vehicle makers. Other half is the rest of that value chain includes support and services, flight operations, ground infrastructure and passenger solutions, all of which need to be successful in tandem [https://www.aviationtoday.com/2019/01/15/airbus-exec-expanding-services-challenging-uber/].

3 to 5 percent of passenger traffic through big cities will be needed to make the business case for urban air mobility, which "be a huge value for society," decreasing congestion on the roads and pushing for improved air traffic infrastructure in the skies. Airbus thinks 2-2.5 times the price of car travel is what it would realistically, but sustainably cost for on-demand air travel based on what the company has seen with Voom and in other cities.

Airbus has hopes for a modular system called Pop.Up (Figure 4.150), consisting of a pod that can attach to both an Airbus-created autonomous, electric rotor rig for flight and an unmanned, electric, Audi-produced wheelbase. The company has released a mockup video showing passengers being picked up from an airport, after which the vehicle would deposit them directly into the Audi wheelbase, allowing the rotor part of the vehicle to detach and the car to take over delivering them to their destination. The air taxi part of the vehicle would have a theorized 60 kW battery powering it, allowing 75 mph flight with a range of 37 miles and a charge time of 15 minutes. Notably, this UAV has no wings.



Figure 4.150: A rendering of the Airbus/Audi modular Pop.Up, with wheelbase and rotor attachments. (ItalDesign)

The message of Eduardo Dominguez-Puerta, Airbus' Head of Urban Air Mobility, at AIAA SciTech in San Diego, California compared the UAM industry to the personal computing industry of the 1970s and '80s, when pioneering manufacturers IBM and Hewlett-Packard were industry giants. Since then, companies like Microsoft that started as software providers for those PCs, have grown and started making their own hardware, a story Airbus is using as a cautionary tale. A major goal of the survey [Woodrow Bellamy III, 2019] was to help transition Airbus from its traditional business-to-business model of manufacturing aircraft to the more consumer-facing style of operations it will need for electric air taxis.

There are 118 companies working on air taxi prototypes, according to Dominguez-Puerta [https://www.aviationtoday.com/2019/01/15/airbus-exec-expanding-services-challenging-uber/]. There was predicted that there will ultimately be room in the market for five or six types. Getting engineers together to come up with a potential configuration will cost around $5 million, which is easy to achieve with the venture capital funding that is flowing into the space.

Safety is their primary concern influencing people's willingness to use eVTOL aircraft. The second highest public perception factor is the type of noise generated by such vehicles, followed by the time of day and altitude at which eVTOLs are flown [Woodrow Bellamy III, 2019]. A total of 385 respondents were asked about the eVTOL operations in each of the four cities targeted as part of the study (Figure 4.151). Respondents in Mexico City were the most welcoming and expressed the highest likeliness to use eVTOLs, with 67 percent of respondents saying they were likely or very likely to use urban air mobility in the future. The study also observed the modes of transportation that people currently engage in, showing the strongest link between likeliness to use UAM and those who use rideshare services such as Uber. Perceived convenience was also highest in Mexico City and Los Angeles, which the researchers believe was influenced by the lower inner city traffic volumes found in New Zealand and Switzerland[Yedavalli P., Mooberry J., 2018].

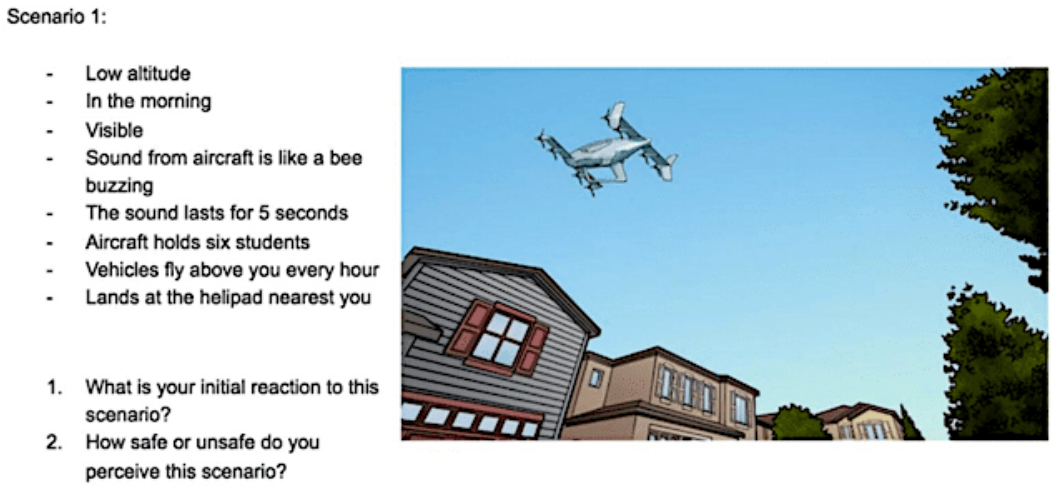


Figure 4.151: Sample scenario for eVTOL operations in each of the four cities targeted as part of the study [Yedavalli P., Mooberry J., 2018]

Among the demographics surveyed, age and income were influential factors in determining respondents' views of UAM as well. Among LA respondents for example, those making more than $150,000 annually had more positive reactions to the future use of UAM. Across all four locations, respondents between the ages of 25 and 34 had the highest initial positive reaction to urban air mobility, with 55 percent of millennials responding positively. The likelihood of respondents to use UAM in the future was also shaped by the length of their existing daily commute. "We asked the typical commute of the respondent and then we used that against their willingness to take UAM, those with average commute of 25 minutes are more likely to use UAM than those with an average commute of 19 minutes,"

[https://www.aviationtoday.com/2019/02/12/public-perception-urban-air-mobility-shaped-noise-safety/].

In addition to ensuring safety, noise mitigation will also be an issue. While UAM aircraft designs are nearly all electric vertical-takeoff-and-landing (eVTOL), the large number of propellers needed to transport people and their belongings results in quite a bit of noise. If hundreds of aircraft are crisscrossing Tokyo, Rome, Karachi, Los Angeles, or any other crowded major city, the already noisy landscape will have an additional cacophony of buzzing aircraft. Silent eVTOL flight isn't in the offing, but designers can utilize technology to make their UAM aircraft as quiet as possible.

The future of aviation and on-demand mobility is arriving rapidly, with groundbreaking advances in technology and airspace integration happening every week. More than 200 companies — including industry-leading names like Boeing, Airbus, Embraer and Bell alongside a number of startups — are racing to develop and certify hybrid and fully-electric aircraft that combine the 'VTOL' of helicopters with the forward-flight efficiency of aeroplanes to create vehicles that will efficiently move people around urban areas for a fraction of the cost of a helicopter today [https://evtol.news/directory/]. Many of these aircraft are harnessing electrical power in a bid to be more environmentally and economically sustainable, with multiple electric vertical takeoff and landing (eVTOL) aircraft taking shape. Other programs are looking beyond electricity to alternative energy sources such as hydrogen fuel cells.

NASA concept vehicles (Table 4.28) that can be used to focus and guide NASA research [Gorton S.A., 2018]:

- Open, publicly-available configurations;
- Provide focus for trade studies and system analysis;
- Push farther than current market trends;
- Provide a range of configurations;
- Cover a wide range of technologies and missions that are being proposed.

Passengers	50 nm trips per full charge/ refuel	Market	Type	Propulsion
1	1 x 50 nm	Air Taxi	Multicopter	Battery
2	2 x 50 nm	Commuter Scheduled	Side by Side (no tilt)	Parallel hybrid
4	4 x 50 nm	Mass Transit	(multi-) Tilt wing	Turboelectric
6	8 x 50 nm	Air Line	(multi-) Tilt rotor	Turboshaft
15			Lift + cruise	Hydrogen fuel cell
30			Vectored thrust	
			Compound	





» Single-passenger (250-lb payload), 50-nm range electric quadrotor



» Six-passenger (1200-lb payload), 4x50 = 200-nm range hybrid side-by-side helicopter



» Fifteen-passenger (3000-lb payload), 8x50 = 400-nm range turbo-electric tiltwing

Table 4.28: NASA-developed Concept Vehicles for UAM

eVTOLs could be used for short-distance parcel delivery. Current prototypes are already carrying payloads of several dozen kilograms. They could help delivery companies solve the logistics problem of the "last 10 miles", which is particularly inefficient due to growing congestion and increasingly restrictive CO_2 and particle emissions standards in our cities. These uses are especially promising since they could be coupled with autopilot or remote-controlled solutions, more readily accepted in the parcel transport market. With current technologies, an all-electric architecture wouldn't be capable of carrying cargo over long distances. Safran is developing electric propulsion technologies for numerous platform types (Table 4.29) - some of which herald a whole new approach to civil aviation [Safran and aviation's electric future, 2019]. Using the same technological building blocks, the company is positioned to address wide-ranging needs and markets.

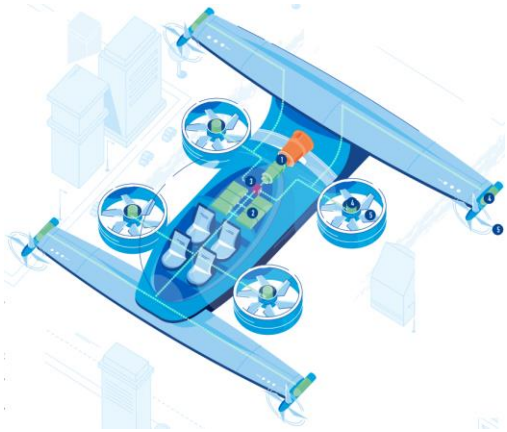
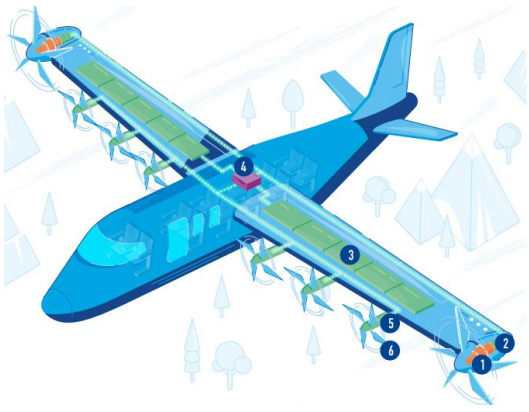
	1Batteries - Primary energy source 2Power management - Distributes electricity to the various systems 3Electric motors - Powered by batteries 4e-Propellers: - Each powered by an electric motor -Provide lift, forward thrust and flight control
	1. Turbo generator - Gas turbine driving an electric generator 2 Batteries - Main or auxiliary power source, depending on the flight phase 3 Energy management - Controls power ratio between the turbo generator and batteries - "Smart" distribution of electricity from the various power sources to the propulsive and non-propulsive systems - Ensures the electric network is stable and protected 4 Electric motors - Powered by the turbo generator, batteries or a combination of both 5 e-Propellers: - Each powered by an electric motor - Provide lift, forward thrust and flight control
	1Turbofan - Main engine for flight phases when a lot of power is needed 2Generator - Converts part of the engine's mechanical power into electricity 3Batteries - Main or auxiliary power source, depending on the flight phase 4Energy management -Controls power ratio between the turbo generator and batteries -"Smart" distribution of electricity from the various power sources to the propulsive and non-propulsive systems - Ensures the electric network is stable and protected 5Electric motors - Powered by the turbo generator, batteries or a combination of both 6e-Propellers: - Each powered by an electric motor -Provide lift, forward thrust (for some phases) and flight control

Table 4.29: Safran-developed UAM Vehicles performances

The age-old dream of the "flying car" is now within reach! Multi-rotor VTOLs able about to carry four passengers could become a reality in the next few years, with numerous projects already in progress worldwide. Safran is involved in some initiatives that are already at an advanced stage, like the Bell Nexus. While it's hard to imagine these aircraft becoming as popular as automobiles, they could serve as a viable alternative in certain areas — like air taxis in and around our congested cities, or air ambulance/medevac platforms, taking advantage of their speed, reliability and quieter operation. For the same reasons, the defense community is also taking an interest for logistics or special missions. Safranis also interested in an other application: small commuter aircraft in the 10-passenger class. Hybrid propulsion architectures could make these planes a competitive proposition for regular routes of a few hundred miles in certain parts of the world [Safran and aviation's electric future, 2019].

VTOLs can be powered by different propulsion systems, ranging from hybrid (conventional combustion engine or gas turbine combined with e-motor) to fully electric powered solutions. Future concepts could also consider fuel cells as the primary energy source. While the different propulsion concepts have different requirements for the infrastructure and landing locations, weight and volume of the propulsion are especially important for aerial vehicles. Leading electric motor suppliers and manufacturers are working on best-in-class power-to-weight electric propulsion systems, capable to perform complete design and development of electric propulsion. This includes Computer Aided Engineering (CAE) supported optimization of the electric motor, with a focus not only on functional aspects, but also on Noise, Vibration and Harshness (NVH) considerations that are necessary to minimize the noise excitation and radiation of the harmonic orders. Furthermore, we are operating dedicated e-motor test cells that enable rapid functional testing of the electric propulsion. E-motor control algorithm design, development and calibration are accomplished with automated testing and a battery emulation system.

An eVTOL is an electric-powered vertical take-off and landing aircraft that can hover, take off, and land vertically. They replace a helicopter's engine and rotors with a distributed electric propulsion (DEP) system that turns smaller rotors. Today, we see three main concepts of eVTOLs with different characteristics and benefits depending on the targeted mission profile, e.g. for intra- vs. intercity mobility:

- Tilt-Thrust: Tilt of wings or rotors for lift and cruise
- Lift and Cruise: Independent propulsion used for lift and cruise
- Multirotor: Wingless with multiple fixed rotors for lift and cruise, tilt of airframe

Compared to a traditional single main rotor helicopter with combustion engine, an eVTOL should be significantly quieter, more reliable and safer and significantly less expensive.

As vertical take-off and landing aircraft are in very early development stages and only few prototypes exist as, hardware benchmarking is yet not possible. Consistent technology assumptions for sizing the vehicles for the UAM mission and market:

- Battery pack modeled as Li-Ion (**TRL 1**)
  - Usable specific energy 400 Wh/kg (well beyond state-of-the-art)
  - Max. mission current 4C, emergency 14C (high end state-of-the-art)
- Wiring and accessory electric systems as fractions (**TRL 3**)
- Structures (**TRL 3+**)
  - Composite VTOL structures, very lightweight booms

- Aerodynamics (**TRL 5+**)
  - Passive rotor and airframe lift/drag
- Propulsion (**TRL 5+**)
  - High Torque/weight electric motors
  - High torque/weight transmissions
- Systems (**TRL 5+**)
  - Equipment for IFR operations (autonomy without additional weight)
  - Environmental control systems, insulation, seating

However, an extensive aerial vehicle database was established containing 80+ aircraft concepts from approximately 60 different Aerial Vehicle manufacturers. This database includes information such as dimensions, weight/payload, range, speed and propulsion. In addition, FEV [https://www.fev.com/en.html] has been performing extensive benchmarking for more than 20 years. With this extensive experience as background, we are also now applying our well-proven tools and methodologies for VTOLs.

According to the Vertical Flight Society's World eVTOL Aircraft Directory [https://evtol.news/directory/], there are already over 200 aircraft concepts currently in development. Industry powerhouses Volocopter, Boeing, Airbus, Bell, Lilium, Beta Technologies and Joby are all working on their own eVTOL concepts. Uber plans to run initial test flights in 2020 and debut commercial aerial services in Dallas, Los Angeles and Melbourne in 2023.

Uber has few specification for the manufacturers of eVTOL aircraft called repeatability [https://evtol.news/?s=Uber+eCRM-001]. The vehicle must be able to operate continuously for at least three hours while flying typical 25 mile (40 km) missions. Uber defines continuous operations as needing to charge around 5-7 minutes between flights, the time it takes to unload and load passengers. The specification of repeatability was made to make sure aircraft manufacturers will design eVTOL aircraft that are capable of making multiple trips during the peak three hours in the morning and evening, when people are going to and from work. Each time the aircraft lands to load and offload passengers, aircraft batteries need to be charged as much as possible, to have enough charge for the next flight and also have enough reserve battery power if a flight plan change occurs mid-flight due to an alternate landing location being required or for an emergency landing. Uber believes that repeatability will be key to maximizing the efficiency and effectiveness of the ridesharing process.

Uber is a big proponent of eVTOLs because of the massive benefits using Distributed Electric Propulsion (DEP, Figure 4.152) for aircraft. Distributed Electric Propulsion simply means that multiple electric engines are distributed along, above, below, within and/or around the wings and/or the fuselage and are powered by electricity. Using DEP can achieve better performance from the aircraft including improving the flying capability in normal and bad weather conditions (each engine can be running at difference speeds to achieve maximum control in wind conditions), increases safety, increases reliability, minimizes noise, increases ride quality, is more fuel efficient (or lower energy use), electric engines/propellers are light weight and compact, is scalable to almost any size, refuels with renewable energy, greatly reduces greenhouse gases and what most of us know, no emissions.



Figure 4.152: GL-10 UAS DEP Tilt-Wing Tilt-Tail VTOL Flight Demonstrator

Uber has stated they have made a first in the aerospace industry by requiring their new aircraft designs to have ultra-low noise specifications built in as a key feature. They are accomplishing this goal using DEP and with a very specific aircraft design element by specifying co-rotating propellers for VTOL flight. Co-rotating propellers means a set of two propellers are stacked one on top of the other, with both propellers turning in the same direction. There are two main reasons why co-rotating propellers are extremely important for aircraft. First, it reduces noise and second, it increases the efficiency of the propellers. Of note, electric powered propellers don't need a warm-up or shut-down period like helicopters or jets, and don't have complicated procedures that airliners have when taxing to or leaving a jetway. eVTOIs don't need any significant taxiing that other aircraft need, allowing take-offs after boarding to take place more rapidly and vice versa. Jetways are not needed for eVTOL aircraft. In fact, jetways can actually pose hazards to any aircraft if not fully retracted before departure and can damage a jetliner. While it is rare, if a jetway is not properly maintained each year, a mechanical failure occurs, or if the jetway has defective parts — jetways have been known to collapse.

The market of eVTOL concepts is broadly diversified, with a common set of technologies such as electric propulsion. More than 80 start-ups and established aircraft manufacturers are currently developing over one hundred eVTOL aircraft concepts. Having extensively reviewed these concepts, one may expect that less than 20 percent are suitable for aerial ride sharing and are developed by credible players which have the capability to drive its concept through full development and certification into operation. Different use-cases are a key driver behind the broad conceptual diversification of the eVTOL aircraft landscape. The main differentiator is the aircraft architecture with the related propulsion concept: It can be distinguished between the multirotor, the lift & cruise and the tilt rotor/wing architecture, Table 4.30. While there are also differences in the energy source, i.e. pure electric and hybrid systems, the following paragraphs focus on the electric motor.

Multirotor (wingless)	Lift & Cruise	Tilt Wing / Rotor
+ Low efforts to flight control	+ Medium energy efficiency	+ Good energy efficiency
+ Inherent redundancy	+ Medium efforts to flight control	+ Effective use of propulsion, no extra weight for carrying temporarily unused engines
+ Low system complexity	+ Gliding possible	+ Gliding possible
− Limited energy efficiency in cruise flight	− Ineffective use of propulsion, extra weight for carrying temporarily unused engines	− More complex design
− Limited flight speeds	− Increased drag in horizontal flight due to rotors (if not retractable)	− High efforts to flight controls
− Limited / no Gliding capabilities		
● 40 concepts	● 20 concepts	● 50 concepts

Table 4.30: Different use-cases are a key driver behind the broad conceptual diversification of the eVTOL aircraft landscape

Performance related requirements differ between the architecture concepts due to different cruise speeds and Maximum Take-Off Weight (MTOW) requirements, but also due to the number of electric motors. Power and torque densities along with the e-motors' efficiencies are very important to aircraft due to their direct effect on the overall efficiency, range, and consequently on the overall mission suitability. eVTOL total battery weight requirements are significantly high that could limit its capability to compete on long missions, Figure 4.153 [UAM Market Study, 2018]. Figure 4.154 provides an overview of the power density of electric motor concepts from suppliers with aviation activities compared to aviation certified piston engine or turbine applications. It shows why distributed electric propulsion becomes so popular for eVTOL, but is also attractive for small general aviation applications, since state-of-the-art electric motors can achieve weight savings compared to piston engines.

The specific power of the conventional aviation electric motors ranges from 0.5 to 2.5 kW/kg, approximately; though some prototypes with a magnitude of 5 kW/kg (Siemens researchers have developed a new type of electric motor that, with a weight of just 50 kilograms, delivers a continuous output of about 260 kilowatts—five times more than comparable drive systems) [https://www.greencarcongress.com/2016/07/20160704-siemens.html] are known. Notwithstanding, turbofan engines have the value of 3-8 kW/kg, which eliminates the possibility of considering the use of traditional electric machines with copper windings as part of the propulsion system. To date, competitive performance can be achieved with the use of superconductor electrical motors, which can have a specific power of 10-15 kW/kg and a specific moment of 35 Nm/kg, which makes them comparable with low-speed turbines [Levin A.V., 2010]. Apart from this, superconducting electrical machines have the following advantages: higher efficiency; smaller values of inductive parameters, smaller noise level, etc. [Dubensky A.A., 2016].

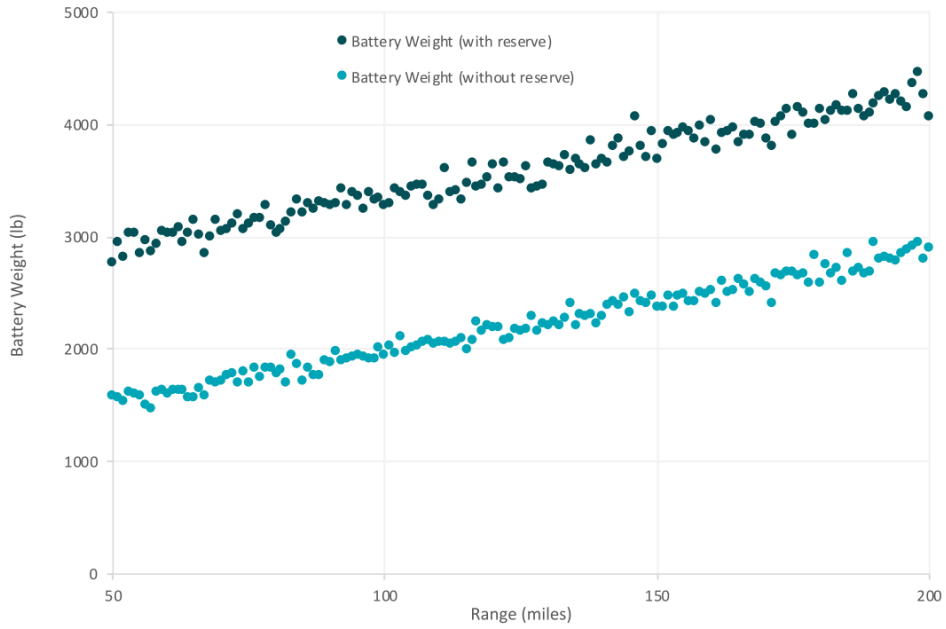


Figure 4.153: Battery weight as function of range [UAM Market Study, 2018]

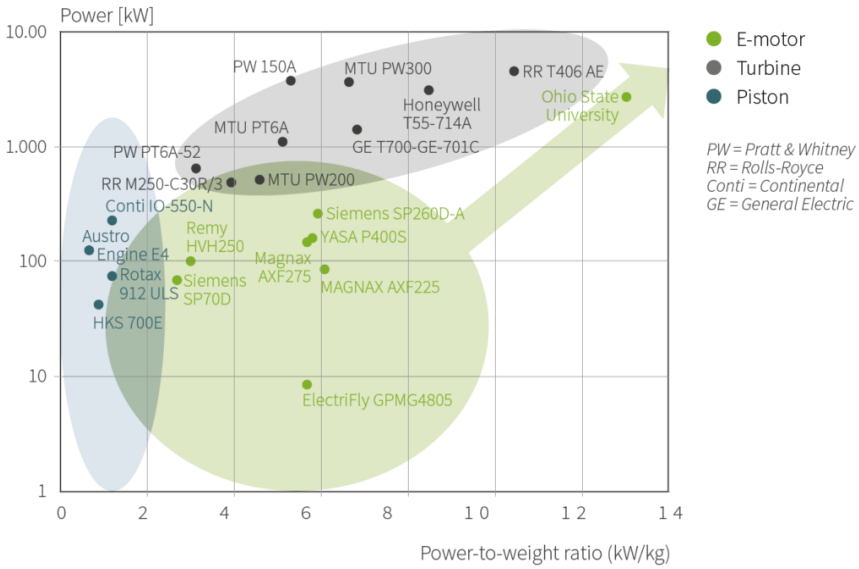


Figure 4.154: An overview of the power density of electric motor concepts from suppliers with aviation activities compared to aviation certified piston engine or turbine application

Fully superconducting electrical machine has recently become the main object of interest for many aircraft power supply systems manufacturers due to their ability to potentially achieve a mass 3 times lower than modern turbofan engines by minimizing losses in both the field and armature windings (Figure 4.155).

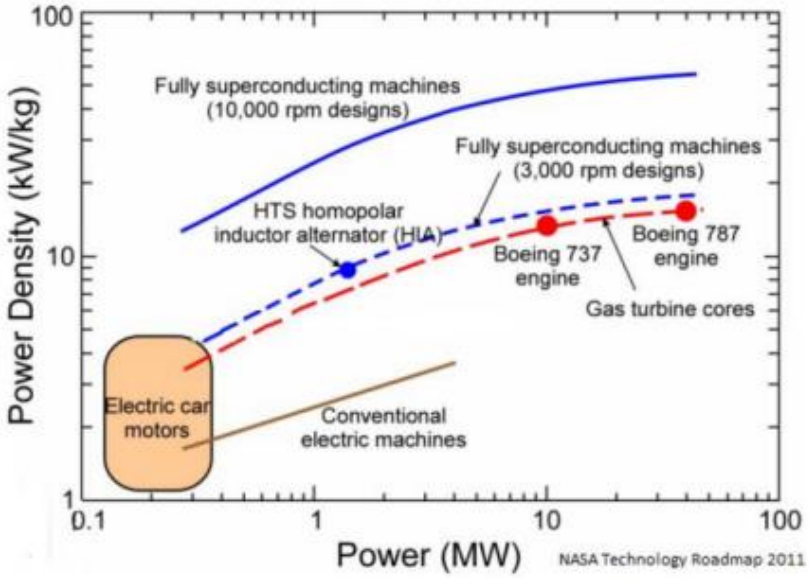


Figure 4.155: Comparative characteristics of electrical machines and gas turbine engines

In addition, electric motors for aviation applications must be highly reliable because malfunctions can directly lead to flight critical emergency situations. Against the background of the operational concept, high availability and long maintenance intervals are required. Since the aircraft are lightweight designs mainly based on composites, the Noise Vibration Harshness (NVH) of electric motors should be at a minimum to avoid transferred vibrations to the fuselage and structural components. Using electric motors for these kinds of new aircraft concepts instead of complex turbines, could offer an opportunity for automotive players with activities in the electrification of powertrains.

Battery technology is advancing rapidly as each year passes, which is a big plus to making future eVTOL aircraft to have equal to and eventually, it is foreseen, to have a better range than its gas-powered counterparts. As newer battery technology is developed, eVTOL aircraft will fly longer in the air, fly further distances and will allow an increased payload weight. In addition, the technology has been created to charge Uber's eVTOL aircraft as quickly as possible during peak times of travel to keep downtime of these electric aircraft to a minimum. One has to only look at the newly created technology of solid-state batteries by universities and corporations around the world, to see the overwhelming benefits of batteries powering electric vehicles. Scientists predict that battery energy storage (called energy density), in the near future, will have enough energy to power electric cars to easily double the range of current internal combustion engine (ICE) ground vehicles, and one can only hope the same results will be seen for eVTOL aircraft.

UAV noise and other environmental factors

At flying altitude, noise from advanced electric vehicles will be barely audible. Even during take-off and landing, the noise will be comparable to existing background noise. It was clear that noise concerns, founded on health and welfare impacts, are complex psychoacoustic issues. It is important to understand the direct environmental impact characteristics of advanced air mobility vehicles. It is just as important to understand the public reaction to these technologies. Public acceptance of advanced air mobility, particularly noise aspects, is perhaps one of the biggest challenges along with safety. Failure to address these issues could hinder advanced air mobility implementation. Air taxis have potential to cause ecological impacts to avian populations in cities, increase risk of bird collisions and other impacts on animals.

Our preliminary first order noise analysis (Figure 4.156) showed that noise exposure is expected to be more severe near the take-off and landing areas. FAA's software system AEDT is used, that models aircraft performance in space and time to estimate fuel consumption, emissions, noise, and air quality consequences. Noise propagation is represented in AEDT with a database of Noise Power Distance (NPD) data, which are specific according to aircraft type, aircraft operation type, and noise metric (and, in the case of helicopters, directivity), combinations of aircraft operational modes (approach, departure, overflight), engine power states and slant distances from receptor to aircraft. Helicopters like Eurocopter 130, Robinson R44 and Robinson R22 are considered to be closest helicopter type to the proposed eVTOLs. For first order analysis, we replicate R22 (2 seats, 2350 lb MTOW) by adding quietness levels of 10 db, 20 db and 30 db. Chart below shows sample NPD curves for Approach [Johnson W., Silva C., Solis E., 2018].

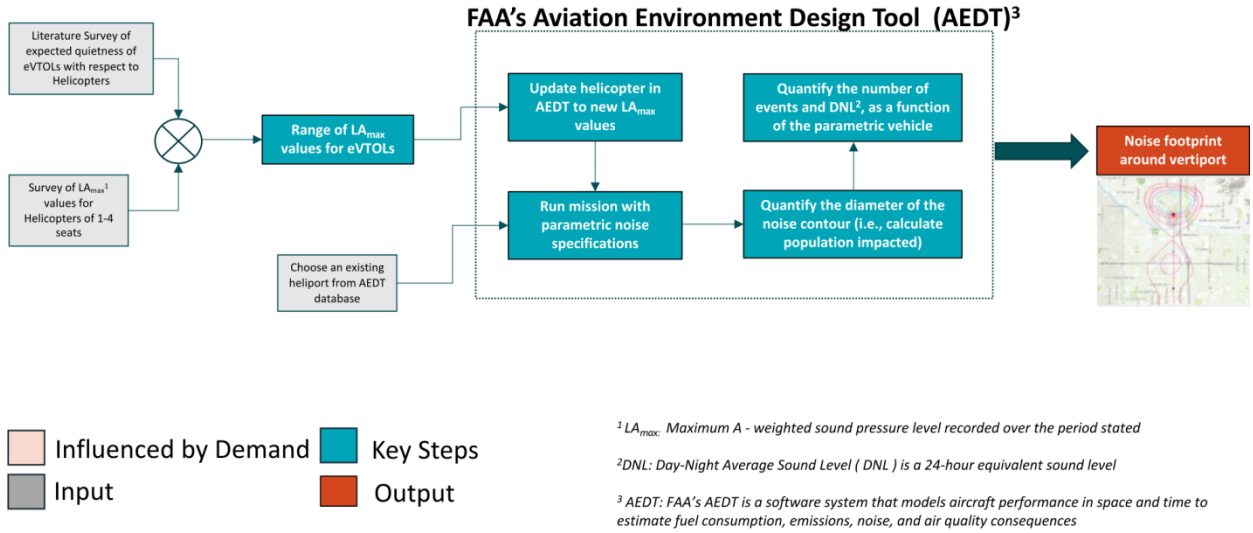


Figure 4.156: First order noise impact modeling for UAV noise assessment [Johnson W., Silva C., Solis E., 2018]

Noise level comparisons are shown for Robinson R22 and its quieter versions in Figure 4.157. Figure shows picture of arrival mode only. Following specifications were followed: Profile type - Approach and Departure; Noise Metrics - L_{Amax}, DNL; Heliport Inn Place, Phoenix; Number of Operations per day 100; Cruise Altitude 1000 ft; Landing Speed 70 mph; Contour Type 65 dBA [Johnson W., Silva C., Solis E., 2018].

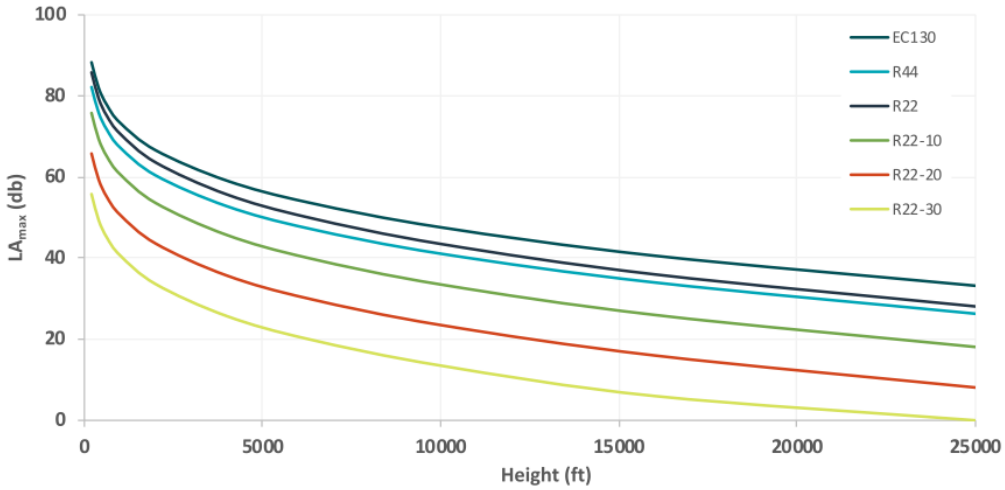
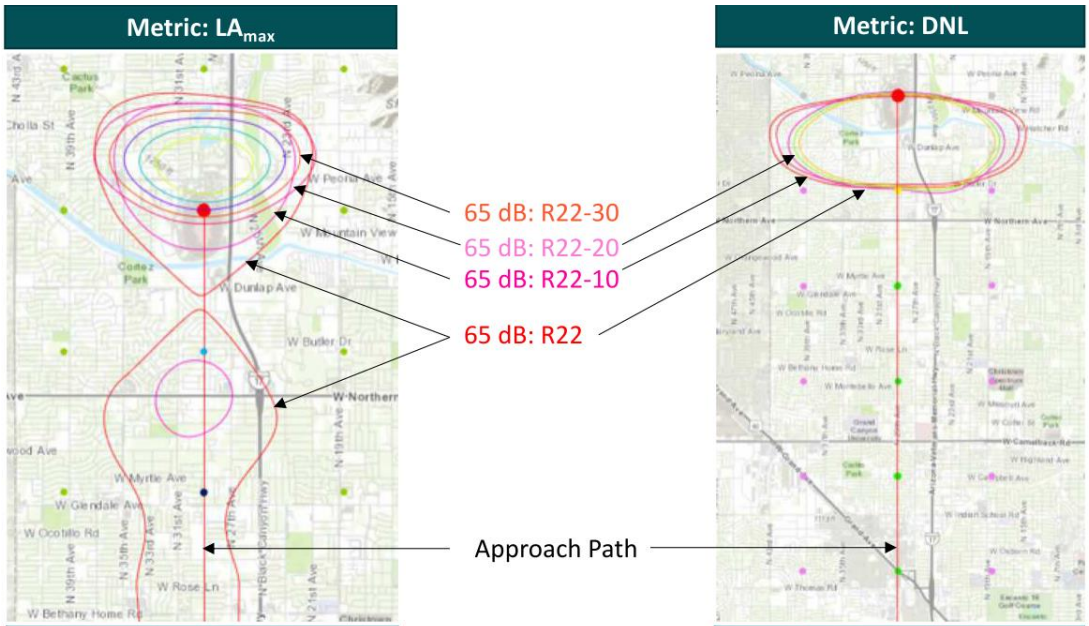


Figure 4.157: Noise Power Distance for small helicopters in AEDT data base

Size of noise contour (Figure 4.158) represents enclosed area exposed to noise levels of 65 dBA and above. It is observed that even in a scenario where the helicopter is 30 dBA quieter than original helicopter (i.e., R22-30), there is small area for arrival and larger area for departure mode around the heliport that experiences maximum noise level of 65 dBA or more`[Johnson W., Silva C., Solis E., 2018].



Helicopter	Contour Area – Arrival (sq. miles)	Contour Area – Departure (sq. miles)
R22	20.88	25.11
R22-10	2.22	17.30
R22 -20	1.80	7.63
R22-30	1.37	7.14

Helicopter	Contour Area – Arrival (sq. miles)	Contour Area – Departure (sq. miles)
R22	5.84	16.07
R22-10	4.95	7.54
R22 -20	4.81	6.61
R22-30	0.00	6.23

Figure 4.158: Noise level comparisons for arrival and departure mode [Johnson W., Silva C., Solis E., 2018]

Also, there are may be ways to mitigate noise impacts while in flight by choosing routes and flying altitude of minimum impact. Urban areas like Washington DC, Los Angeles and Miami have most of their operations in areas of high background noise (greater than 50 dB as defined by Federal Highway Administration, Figure 4.159). Public acceptance to Air Taxi operations in these urban areas may be higher in comparison to New York, Hawaii or Denver [Johnson W., Silva C., Solis E., 2018].

US Department of Energy and Environment Protection Agency (EPA) estimates a vehicle's impact on climate change in terms of the amount of GHGs, mostly carbon dioxide CO_2. Tailpipe emissions and upstream emissions include CO_2, methane, and nitrous oxide emitted from all steps in the use of a fuel, from production and refining to distribution and final use—vehicle manufacture is excluded. Our first order analysis shows that a 5 seat eVTOL (at 75% load factor) is expected to generate ~2 times more CO_2 emissions per passenger mile 1 when compared with Tesla Model S 75D (1.54 persons per vehicle), but 35% less than Eurocopter EC 130 in the worst case scenario (Figure 4.160) [Johnson W., Silva C., Solis E., 2018].

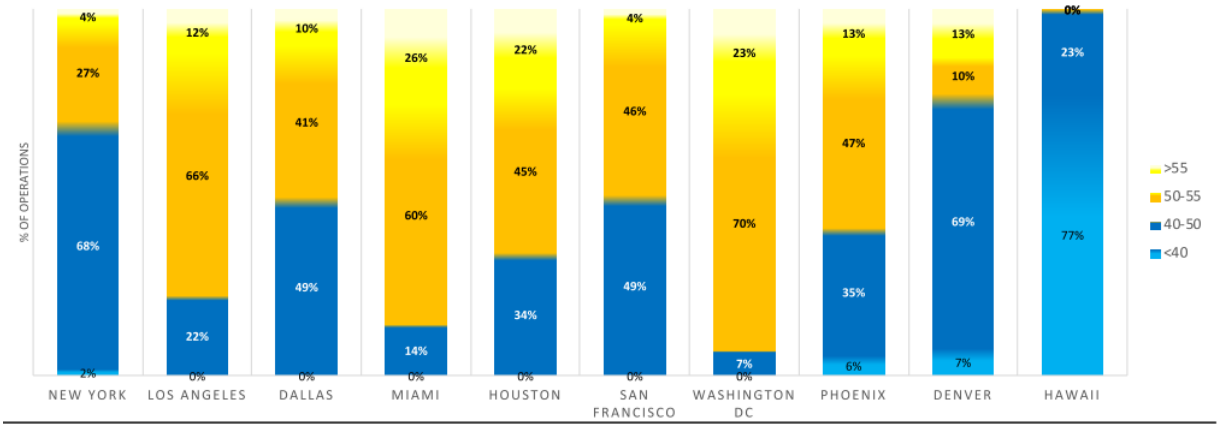


Figure 4.159: Large percentage of operations are in the areas of low backgroundnoise [Johnson W., Silva C., Solis E., 2018]

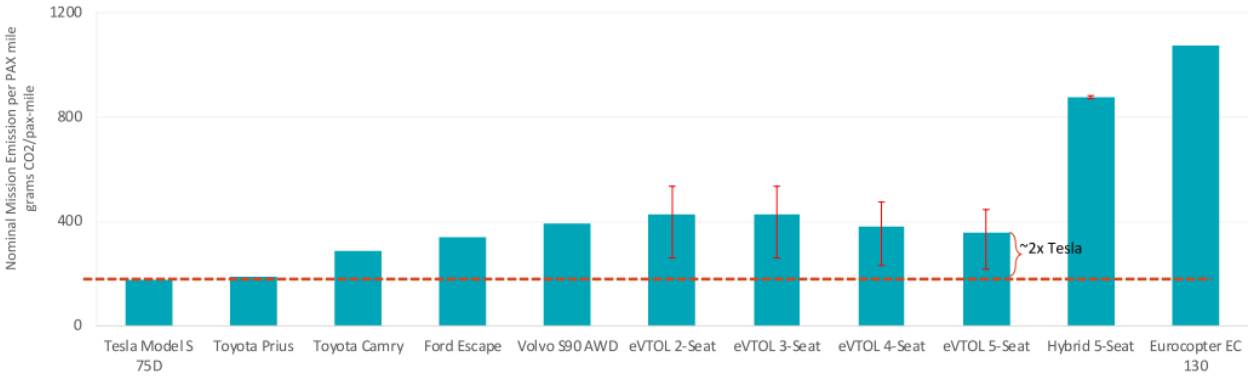


Figure 4.160: Well-to-wake greenhouse gas (GHG) emissions [Johnson W., Silva C., Solis E., 2018]

Noise from aircraft, and other transportation modes, is a complex topic spanning acoustics, the physiological way humans experience noise, and the psychological perceptions listeners have of the source of the noise and what it represents to them. A large body of research spanning this area has been conducted over the last century, with learning outcomes relevant to modern aviation [M. Basner, et al., 2017; National Research Council, 2002].

Three key constraints were identified by [Vascik P. D., 2017] that may impact the development, implementation or operation of ODM Aviation networks in the near or far-term. These constraints concerned the availability of ground infrastructure, the capacity of air traffic control to manage significantly increased

flight densities at low altitude, and the local community's acceptance of noise generated by ODM aircraft. Takeoff and Landing Areas (TOLAs) are likely to be located within urban and suburban areas bringing aircraft operations in closer proximity to people than experienced at current airports. Aircraft noise may make On Demand Mobility (ODM) operations susceptible to nuisance or government takings lawsuits. Aircraft noise may restrict access to TOLAs in specific geographic areas or during certain times of day (Figure 4.161).

[Vascik P. D., Hansman R. J., 2017] reviews how nuisance, trespass, government takings and a variety of other legal mechanisms may potentially restrict low altitude flight due to noise concerns. Figure 4.162 displays the wide variety of regulatory pathways through which aircraft noise may result in operational restrictions. It should be noted that there are numerous stakeholders involved in this process, many of them elected officials or subordinate to elected officials, who have parallel pathways to impact aircraft operations. As a result, ODM Aviation may have to work with each of these stakeholders, or reduce the impact of aircraft noise on the public itself in order to mitigate this constraint.

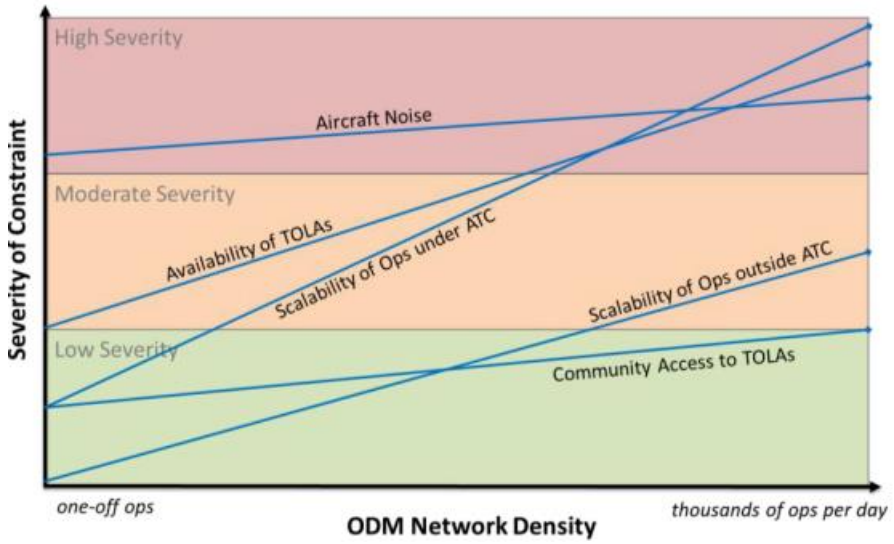


Figure 4.161: Notional dependence of ODM constraints on network density [Vascik P. D., 2017]

The impact of aircraft noise can be mitigated through two fundamental approaches that may be generally considered as new noise reducing technologies and operations:

- *Technologies*: Develop and implement new aircraft technologies that either reduce the source noise emissions from the vehicle, or reduce the annoyance of the noise generated to bystanders on the ground.
- *Operations*: Operate the vehicle in a manner such that it either produces less total noise, or such that the noise is emitted in a location or way that causes less annoyance to bystanders on the ground.
- Noise exposure/impact impact reduction at the destination through *compatible land use and urban development*
- Noise exposure/impact reduction through operational restrictions such as *flight quotas, noise limits, or curfews.*

The FAA responds to noise complaints for aircraft or helicopter operations at low altitudes by working with airports to create noise sensitive approach and departure routes, limit airport hours of operation, or exclude some vehicles or operations from an airport [Los Angeles World Airports, 2010]. Beyond noise generation regulations levied on the vehicles, voluntary or temporary noise reduction measures are common mechanisms employed to reduce the noise impacts of flight without the need for regulation. The FAA frequently creates Temporary Flight Restriction (TFR) areas around special public events (such as concerts or

sporting events) that prohibit unauthorized low altitude flight in the area for noise reduction and safety purposes. The FAA has also created voluntary helicopter routes, airport transition routes, and VFR flyways that reduce the impact of aircraft noise by concentrating flights over less noise sensitive areas such as highways or industrial parks.

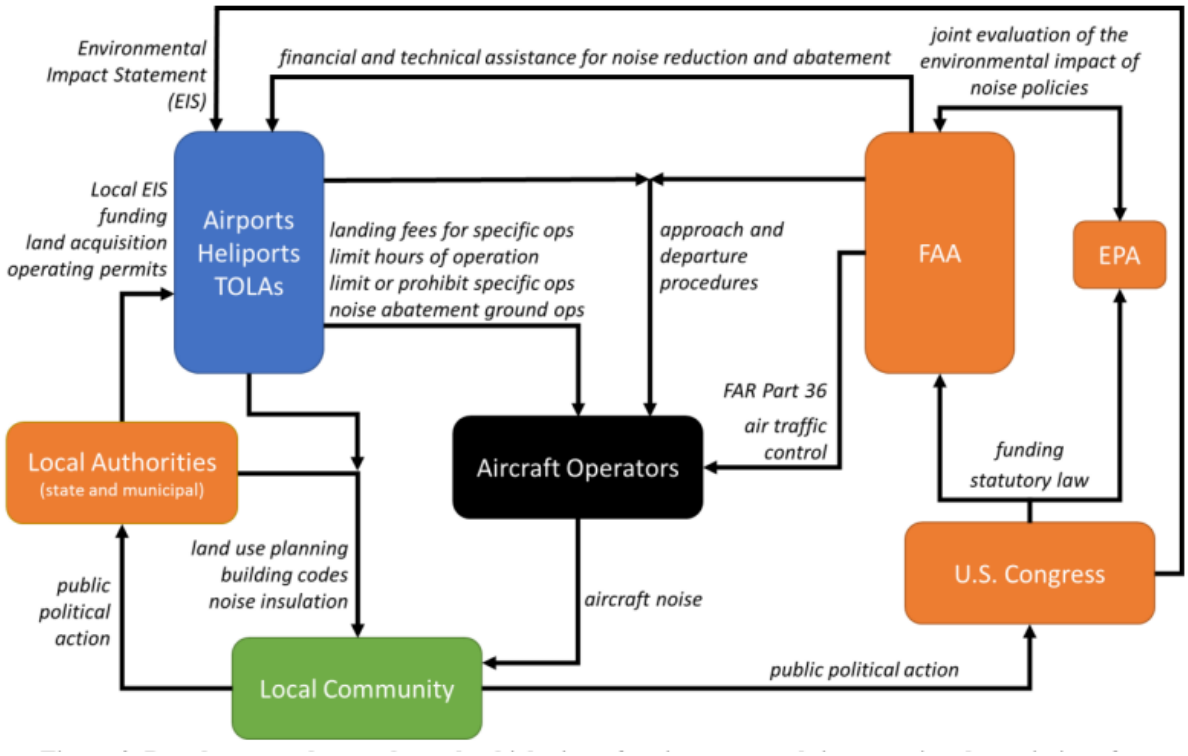


Figure 4.162: Regulatory pathways through which aircraft noise may result in operational restrictions for aircraft operators. Image developed from information in the FAA Airport Compliance Manual and the 1976 Aviation Noise Abatement Policy III.3.a-e [Vascik P. D., Hansman R. J., 2017]

A significant amount of interest and excitement has been expressed by the ODM community concerning the potential for new technologies incorporated in ODM aircraft to significantly reduce total noise emissions. The recent Uber white paper on ODM Aviation[Holden J., Goel N., 2016] provides a significant amount of detail on various noise metrics for aviation, quantitative noise goals for ODM aircraft (expressed with these metrics), and the proposed technological means by which to reach them. Table 4.31 displays a summary of the new technology-based mitigation proposals from this white paper as well as other authors.

Technology	Description
Electric Motors	Replacing piston or turbine aircraft engines with electric motors removes most mechanical, combustion and exhaust noise sources. Furthermore, electric motor power density is scale invariant, therefore 1-2 passenger aircraft may be developed with significantly reduced takeoff weight reducing thrust and lift and drag requirements resulting in lower noise generation. Finally, and most significantly, electric propeller tip speeds may be up to 50% lower than helicopter rotor tip speeds dramatically reducing noise but maintaining efficiency
Distributed	Aircraft utilizing small, distributed electric propulsors are able to achieve comparative vehicle performance to helicopters while capturing a variety of acoustic benefits. The

Propulsion	small propellers may be operated with slower tip speeds (reducing noise) and at higher RPM to avoid low-frequency noise generation. It should be noted that while high-frequency noise is rapidly attenuated by the atmosphere as compared to low-frequency noise, it is more disagreeable to bystanders at close range. Finally, some propellers may be de-powered (and potentially folded) during cruise to reduce noise generation.
Frequency Spectrum Spreading	On-going research by NASA is investigating if operating distributed propulsors at slightly different speeds may spread the emitted frequency spectrum in a manner that reduces the perceive noise annoyance of bystanders.
Tiltrotor, Fixed Wing Aircraft	Tiltrotor capabilities enable VTOL while avoiding edgewise flow over the rotors during forward flight (as the vehicle cruises in a fixed-wing configuration). This reduces required rotor speed and reduces noise. Cruise in a fixed-wing configuration also reduces thrust requirements compared to vertical lift configuration further lowering noise.

Table 4.31: Technology-based ODM aircraft noise reduction proposals

1) Noise Objective for the Vehicles

Achieving VTOL noise levels similar to ground transportation is essential for widespread VTOL adoption. Medium-sized trucks traveling through neighborhoods at speeds of 35 to 55 mph 28 generate sound levels of 75-80 dB(A) sound pressure level (SPL) at 50 feet, which are roughly perceived to be acceptable by a listener at an average distance in adjacent buildings. We estimate this figure to be half as loud (10 dB less) as the smallest four-seater helicopter in operation, the Robinson R44, which (having certificated noise emission levels of 81 dB sound exposure level SEL at 500 ft altitude) is about 87 dB at 250 ft altitude.

However, given that a VTOL network would deploy a fleet of potentially hundreds of aircraft, we understand that so many simultaneously operating VTOLs would also not be acceptable at noise levels merely equal to trucks. As such, we feel that a reasonable goal for vehicles is half that of medium-sized trucks today—67 dB(A) at ground level from a VTOL at 250 ft altitude, which appears from early analysis to be achievable. For context, this is comparable to a Prius at 25 ft from the listener, driving by at 35 mph.

NASA RVLT project research areas for UAM: low tip speed; rotor shape optimization; flight operations for low noise; aircraft arrangement/interactions; cumulative noise impacts from fleet ops; active noise control; cabin noise; metrics and requirements. For aircraft with two or more main rotors, interactions between the rotors have a significant impact on performance, vibration, noise, and handling qualities. The interactions depend on the arrangement of the rotors. Figure 4.163 illustrates the wake geometry of the quadrotor and side-by-side aircraft in cruise flight [Johnson W., Silva C., Solis E., 2018]. The overlap of the side-by-side rotors significantly improves the efficiency of cruise flight. Rotor-rotor interactions, such as rear rotors operating in the wake of front rotors, and wake interactions on retreating sides of overlapped side-by-side rotors, will increase blade-vortex interaction noise. Blade shape and spacing can be optimized for low blade-vortex-interaction and high-speed-impulsive noise. Active control of rotor noise can achieve significant noise reductions, with 6 to 12 dB reduction demonstrated through analysis, wind tunnel test, and flight test of rotors.

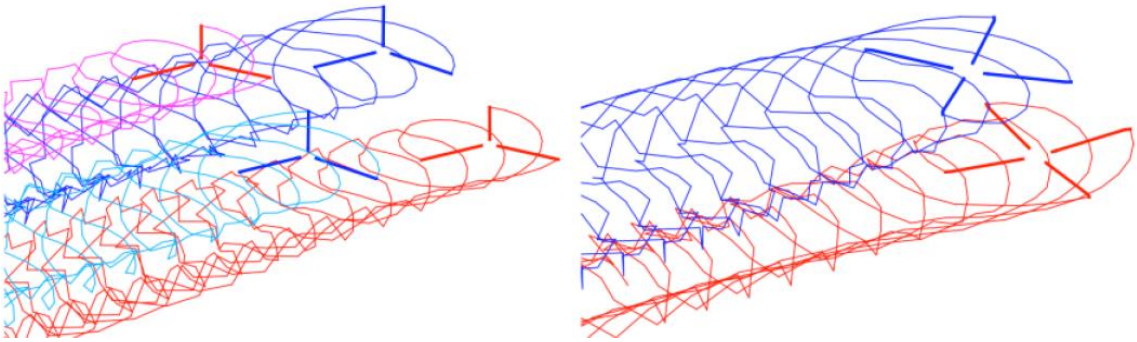


Figure 4.163: Wake geometry of quadrotor and side-by-side aircraft at cruise speed [Johnson W., Silva C., Solis E., 2018]

UAM vehicles have the potential to alter the community soundscape due to their noise characteristics that are qualitatively different from traditional aircraft. [Christian A, Cabell R., 2017, Senzig DA, et al., 2018, Rizzi SA, et al., 2017].In addition, similar to sonic booms from supersonic aircraft en route, the UAM noise may not be concentrated around traditional airports. There is very little scientific research on the human impacts of noise from UAM aircraft, although there have been increased efforts to measure and model the noise generated by them and their components. [Bulusu V, Polishchuk V, Sedov L., 2017; Huff DL, Henderson BS, Envia E., 2016; Zawodny NS, Christian A, Cabell R., 2018].

2) Long-term Annoyance

Sound pressure level alone is necessary but insufficient to specify the noise parameters that should govern VTOLs. This is due to the concept of annoyance, a phenomenon associated with the physiological perception of loudness, duration and repetition. Two different kinds of annoyance responses are triggered in people: (1) some notice individual disturbing events that they remember, and tend to count how many times this disturbing event has happened, and (2) others assess noisiness of an area by averaging noise over the long-term, expressing their assessment as, for example, a "busy or "noisy" neighborhood. "Busy" or "noisy" often equates to lower property values when compared with "quiet" neighborhoods. Short-term noises also create individual alerting events and can awaken people from sleep.

Fortunately, there are established methods for measuring annoyance. Since the development of turbofan jet airliners, cities and the FAA have worked on the long-term noise issue, which has led to the creation of the Day Night Level (DNL). DNL is the averaged sound pressure level for a 24-hour period, with a sensitivity offset of 10 dB between 10 PM and 7 AM, so a constant sound of 70 dB(A) in the daytime and 60 dB(A) at night would define a neighborhood with 70 dB DNL. The FAA uses a yearlong running average of DNL when reporting the noise impact of airports. Day Night Level guidelines differ by type of neighborhoods. For example, targets in industrial neighborhoods are not as stringent as those for residential or suburban areas. As VTOLs begin operation it will be valuable to characterize the ambient noise of landing sites individually, rather than using arbitrary targets. Doing so would be operationally very powerful as this will enable operations to be sensitive to the characteristics of each take-off and landing location and contribute only the amount of additional noise that won't disturb the neighboring community. To achieve more tailored and responsive noise levels at vertiports and vertistops, operators will compute the maximum number of operations of each vehicle that can be conducted at each site while not increasing the long term average Day-Night Level (DNL) by more than 1 dB, which is the smallest change in loudness that a person can detect.

3) Short-term Annoyance

While long-term annoyance is measured in DNL, short-term annoyance is typically measured (around hospital heliports, for instance) with single event noise equivalent level (SEL or SENEL) metrics, which attempt to capture the likelihood that an individual takeoff or landing will disturb everyday activities like

speech or sleep. The target for short-term annoyance that has been used in hospital heliport studies is for events not to increase the number of night-time awakenings by more than 10%. This is typically predicted using SEL, which is the A-weighted sound pressure level lasting one second that contains the same energy as an entire aircraft event such as takeoff or overflight. A 70 dB(A) sound lasting for two seconds would produce 73 dB SEL; if it lasted for four seconds it would be 76 dB SEL. For a simple event that rises to a maximum and then drops, the duration is the time from the instant the sound reaches 10 dB less than its maximum, to the time when it drops below that same 10 dB less than maximum value. If VTOL vehicles are able to achieve the absolute noise goals as stated above (67 dB(A) at 250 ft altitude), it will be possible to be more optimistic in reducing the percentage increase of night-time awakenings from operations. Because 36 there is a direct statistical relationship between loudness and awakenings, decreasing FICON's guidance for maximum night-time awakenings (10%) to half that—5%—should be achievable.

A study [Christian A, Cabell R., 2017] was conducted by NASA to evaluate human annoyance to sUAS noise, including the effect of variation in operational factors and a comparison of annoyance tonoise from road vehicles. The noise from four commercially available sUAS and four road vehicles, ranging in size from a passenger car to a step van, were recorded and presented to test subjects in a specialized simulation facility. For this limited set of noise sources, a systematic offset was found that indicates the noise of sUAS is more annoying than noise from road vehicles when presented at the same loudness.

Another NASA psychoacoustic study [Rizzi SA, et al., 2017] concentrated on annoyance to noise from a simulated distributed electric propulsion (DEP) aircraft. Using auralizations from noise predictions of spatially-distributed, isolated propeller noise sources, the subjective study in a specialized psychoacoustic facility found that the number of propellers and inclusion of time-varying effects were significant factors in annoyance, while variation of the relative revolutions-per-minute (RPM) between propellers was not significant. The study also developed an annoyance model based on loudness, roughness, and tonality for predicting annoyance to these DEP sounds. Despite the limitations in prediction methods and simplifications, the study identified the relevant parameters and metrics that should be studied further.

4) Site-level Analysis and Tailoring

Identifying metrics that are as vehicle platform-agnostic as possible is an important consideration. Several design approaches for electric VTOLs have already been built and tested, at least three with manned flights and many more in scale or static tests. While details are not publicly available, we know that the different design approaches have significantly different acoustic signatures. This variety of designs makes it challenging to define quantitative noise measurements that are strictly neutral. Simple sound level measurements to compare two sounds aren't accurate when the spectral character of the sounds is different.

Due to developments in the field of audio encoding, today there is a much deeper understanding of the physiology of loudness than there was even a decade ago. MP3 coding and other compressed audio formats depend on being able to discard portions of a sound waveform that we don't perceive. Research in this area has put a sharp point on discoveries made by sensorineural researchers decades before, and gives us confidence that our proposed quantitative noise measurement metrics will accurately predict community response to the acoustic component of VTOLs' presence. For instance, we are careful to use metrics that capture the additional annoyance of a prominent tone or whine from some electric motors, which makes the sound louder than a sound level meter would indicate.

The overall amount of noise and downwash developed by a VTOL is driven by how much thrust it needs to generate for takeoff and landing. To achieve the lowest possible community noise, a VTOL's passenger capacity needs to be limited so that noise and downwash are not excessive. This capacity is well matched to potential on-demand urban air transportation use cases and similar in nature to cars, which typically only carry one to four people. Downwash scales with weight of the vehicle, because it is directly related to the amount of air the propulsion system must accelerate. Noise likewise scales with power, approximately 3 dB

for every doubling of weight, which is reflected in existing helicopter noise rules. But people on the ground are not likely to care whether it is a light or heavy helicopter, only the noise exposure or downwash wind that each event produces.

Besides the main rotor, helicopters have several other noise sources: the tail rotor, engine, and the flow interaction between the rotors and their wakes. Because these noises are in different frequency bands, the resulting loudness is higher than if they were clustered together as is the case for DEP. Physiological loudness is significantly greater for widely separated frequencies than for frequencies grouped closely together, and wide-bandwidth sounds are perceived as being louder because the ear processes each band of frequencies as a separate noise source. Having this combination of noise sources makes it difficult to develop approaches with traditional helicopters that could drop the noise level to the background level of a freeway or other urban location. Electric DEP VTOLs don't have fuel-burning engines, and use variation of torque across multiple rotors instead of a tail rotor for yaw control.

Once the noise emissions of each vehicle are characterized, the next activity is to project how many operations at what time of the day or night will result in reaching the 1 dB DNL increase threshold, or the 5% awakening-increase threshold in the community. This requires integrating the emission of each vehicle (the sound leaving the vehicle) and its distance from the community (determined by the path loss in the air) so that the immission (the sound reaching the listener) of the noise at the closest community point can be predicted. Real-time tracking of site noise will permit documentation that target noise levels are not exceeded, and that thresholds can be adjusted if the noise background changes. A quieter vehicle means more operations are possible at a given site. While computationally difficult a few years ago, this analysis is practical and low-cost today. This approach to site-level analysis will enable operators to measure and tailor noise requirements not only by vertiport/stop, but also enable us to adapt dynamically to operations at the level of specific sites. Doing so would be an efficacious approach to aircraft-related noise measurement and management, which we believe will enhance the capacity for quiet and efficient VTOL network operations in and around communities.

Admittedly, noise from advanced aerial mobility vehicles will be different from noise from commercial aircraft or helicopters. Many of these vehicles will be powered by electric motors, which will be inherently quieter than jet engines or rotorcraft. However, aircraft noise originates from many sources including aerodynamic sources, propeller or rotor blades, and the complex and highly dynamic interactions between these. Electric propulsion does enable new propulsion possibilities that promise to change the character of aircraft noise and to reduce it overall. The degree to which this falls below the public's threshold for annoyance remains to be determined and depends on additional operational and contextual factors. Annoyance caused by noise is not strictly related to noise levels. "New noise," that is noise in places where there was no noise before, causes high levels of annoyance to the public that experiences it. So it is to be expected that the introduction of advanced aerial mobility vehicles will lead to annoyance and adverse health and welfare effects. Understanding the nature of these effects is critical to successfully mitigate them.

Enhanced UAM may include operations with a less intense acoustical impact on bystanders (e.g., less frequent operations in rural areas) and with strong positive social impact (e.g., emergency medical services, search and rescue, and disaster relief). These applications can be a valuable testbed to learn and refine low-noise operations as well as to actively shape positive public perception of the technology [Advancing Aerial Mobility, 2020].

In addition to the potential benefits of these new technologies, performance characteristics unique to some of the new On-Demand Mobility (ODM) aircraft designs may allow them to be operated in ways that also significantly reduce bystander noise exposure. For example, the HAI Fly Neighborly Guide recommends that helicopters utilize takeoff and descent profiles that are as steep as practicable in order to limit low overflight of neighboring properties and bystanders. Various cities in California have already created legislation to shut down helicopter operations above them by limiting helipad construction and usage. This is largely because of

the noise. While helicopters have typically avoided extended vertical (or extremely steep) ascent and descent profiles due to vortex ring state (settling with power) concerns and autorotation safety, new distributed electric propulsion ODM aircraft may be able to execute these maneuvers safely. Table 4.32 displays a set of operations to reduce noise that are currently recommended for helicopters that new ODM aircraft and operators may be able to execute more effectively.

Operation Attribute	Description
Cruise at Higher Altitude	Due to their higher anticipated cruising velocity compared to helicopters, the relative velocity differential between ODM aircraft and fixed-wing aircraft operating at mid to high altitudes over metropolitan areas will be reduced. As a result, ODM aircraft may be approved by ATC to operate in higher altitude, controlled airspace above many metropolitan regions reducing their ground noise signature. In contrast, the lower reaches of these airspaces are typically considered as maximum altitude ceilings for helicopter operations.
Extended VTOL Ascent and Descent	If ODM aircraft with DEP do not exhibit vortex ring state susceptibility during rapid descent, then these vehicles may be able to operate true vertical ascent and descent profiles reducing low altitude overflight near TOLAs.
Avoid Impulsive Noise Generation	Tiltrotor ODM aircraft are likely to avoid impulsive noise generation (blade slap) during sharp maneuvers or high speed descent if they operate in a fixed-wing configuration for these mission segments.
Avoid Noise-Sensitive Areas	While many current helicopter charter flights operate for tourism purposes and frequent populated areas or iconic structures at low altitudes, ODM missions are generally for transportation and may be routed to avoid these areas. Furthermore, aircraft may engage in "ambient noise masking" by flying along routes of significant ground noise generation such as highways or industrial areas [Holden J., Goel N., 2016].

Table 4.32: Noise reduction operations enhanced by potential ODM aircraft capabilities

Analysis of configurations and flight operations have resulted in generalizations for low noise trajectories with applying new, fast acoustic rotorcraft tools to UAM vehicles, including constraints for safety and passenger comfort, incorporating real-time noise awareness into flight controller and at final stage - exploring control of noise exposure through phase control. These will be incorporated into the Fly Neighborly information and upcoming workshops. Developed low noise flight procedures to minimize the impact of helicopter operations. NASA and the FAA tested 6 helicopters in order to develop general "rules of thumb" for low noise flight procedures:

- R-44 and R-66 were tested at Eglin AFB in both steady and dynamic flight conditions with all priority points acquired.
- Bell 207L, Bell 407, AS350, EC130H were tested at Amedee Airfield with all priority points acquired.

Analysis of configurations and flight operations have resulted in generalizations for low noise trajectories with applying new, fast acoustic rotorcraft tools to UAM vehicles, including constraints for safety and passenger comfort, incorporating real-time noise awareness into flight controller and at final stage - exploring control of noise exposure through phase control. These will be incorporated into the Fly Neighborly information and upcoming workshops. Developed low noise flight procedures to minimize the impact of helicopter operations. NASA and the FAA tested 6 helicopters in order to develop general "rules of thumb" for low noise flight procedures:

- R-44 and R-66 were tested at Eglin AFB in both steady and dynamic flight conditions with all priority points acquired.

- Bell 207L, Bell 407, AS350, EC130H were tested at Amedee Airfield with all priority points acquired.

Analysis of configurations and flight operations have resulted in generalizations for low noise trajectories (Figure 4.164). These will be incorporated into the Fly Neighborly information and upcoming workshops. The data will be used to calibrate NASA tools and contribute to the development of real-time acoustic information as a cockpit display.

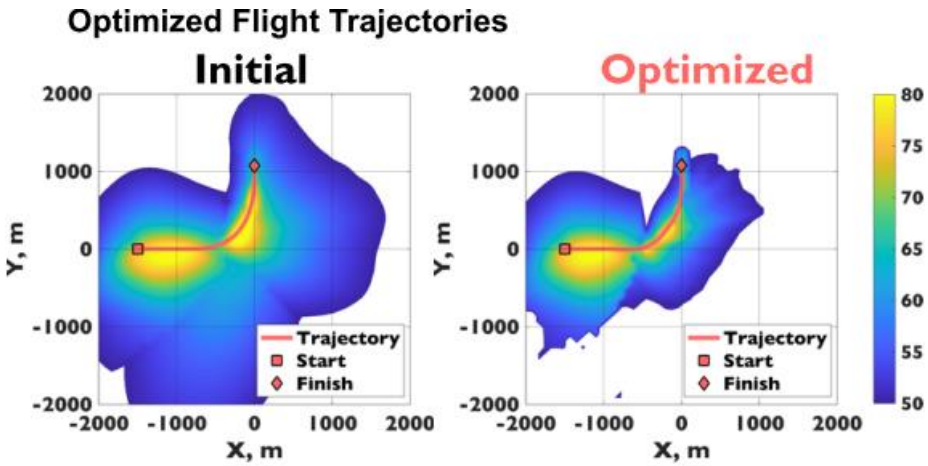


Figure 4.164: Low noise trajectories for R-44 helicopter

Road map for UAV/UAM noise assessment in NASA during next 5-years period is shown in Figure 4.165. It covers all the aspects described above for UAV/UAM noise.

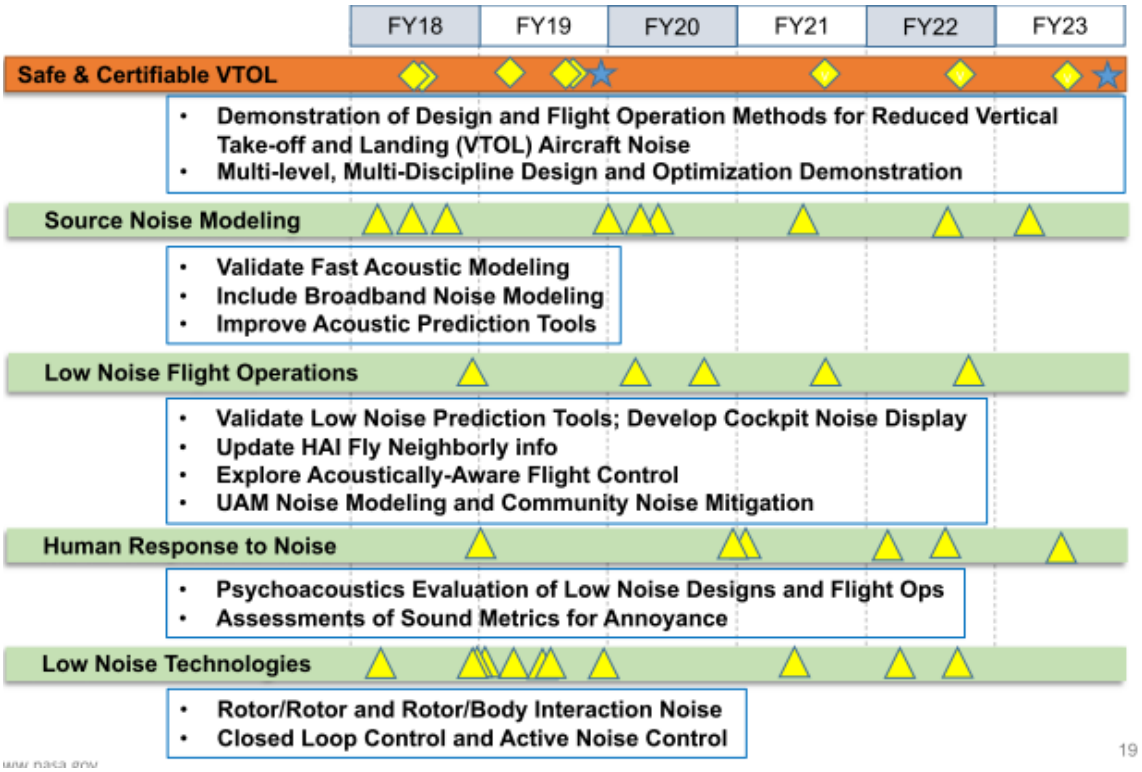


Figure 4.165: NASA UAV/UAM Noise Research Roadmap

Conclusions for UAM noise

Aircraft noise was determined to be perhaps the most significant near-term constraint for ODM Aviation operations. Noise emissions from aircraft and helicopters have historically been the most protested community impact of airports. Such public action has frequently placed pressure on regulatory authorities and government entities to limit or prohibit some aviation operations. As a result, aircraft noise from ODM aircraft was anticipated to indirectly influence the location and operation of TOLAs, the type of aircraft that may be used, and the market demand for ODM Aviation services.

Two categories of potential noise mitigation techniques were explored in this thesis. First, technology-based mitigations including electric motors, distributed propulsion, frequency spectrum spreading and tiltrotor configurations were reviewed. These technologies were found to represent a noise reduction potential over current helicopters. Furthermore, these technologies increased the effectiveness of the second category of noise reduction techniques referred to as operational-based mitigations. Due to unique aircraft performance capabilities, new ODM aircraft may be able to fly at higher cruise altitudes, conduct extended vertical ascents and descents into and out of TOLAs, avoid impulsive noise generation, and bypass noise sensitive communities. These operational-based mitigation techniques have the potential to further reduce the impact of aircraft noise to bystanders on the ground.

Emissions from the UAM

Urban communities are understandably concerned about pollution from lead in fuel and particulate emissions given the wide range of transport solutions in and above their cities. Any new mass-scale form of urban transportation should clearly be ecologically responsible and sustainable. Fully electric VTOL designs provide a compelling solution; they generate zero in-flight carbon emissions and provide a pathway toward significantly lower carbon emissions as utilities adopt renewable energy solutions such as wind and solar [Holden J., Goel N., 2016].

VTOLs represent a potential new mass-scale form of urban transportation.As such, they should clearly be ecologically responsible and sustainable. When considering helicopters as the starting point, there is a substantial opportunity to reduce emissions. Cleanest VTOL is not just a cleaner helicopter, applied to them the best available technologies Found ways to reduce emissions by more than 50% (**TRL 5+** by 2020):

- More attention to drag: faired hubs, landing gear;
- More composites, bonded instead of fastened;
- Advanced drive systems materials and approaches;
- Coaxial and side-by-side helicopters for efficiency;
- LCTR2 heritage for high efficiency civil tiltrotors (HECTR);
- Advanced turboshafts for Classes B and C;
- Li-ion and Fuel Cell for Class A, hybrids for B (Below **TRL 2**).

We consider both the operational emissions of the vehicle, i.e. emissions produced by the vehicle during its operation, and lifecycle emissions, which accounts for the entire energy lifecycle associated with the transportation method, including (in the case of electric vehicles) the production of electricity to charge VTOL batteries. Among the advantages of electric propulsion designs is that they have zero operational emissions. This leaves energy generation (which today is still largely coal, natural gas and petroleum-based) with its associated emissions as the primary concern.

First, all-electric vehicles get their energy from the grid, so there is a high degree of centralization of the energy source versus hydrocarbon fuels. This means the true life-cycle vehicle emissions are highly linked to utility emissions (both the legacy electricity as well as the emerging electricity plants). Second, while 90% 44 of all grid electricity generation today is powered by hydrocarbon fuels (petroleum, natural gas, or coal),

development of new renewable electricity generation (wind, solar, and hydro) is outpacing development of new petroleum/coal sources by a factor of more than two, based on 2016 data (see chart below). Third, electric vehicles (of all kinds) will increase demand for electricity, which will help create the motivation to move toward renewable grid sources, and the electric utilities becoming more CO_2 responsible.

The factors impacting life-cycle emissions for transportation include not only emissions of the energy source, but also the inherent vehicle energy required per mile per person. Due to electric motors being approximately three to four times more efficient than either internal combustion or small turboshaft engines, the actual vehicle energy used is substantially decreased compared to existing small aircraft and helicopters. The integration freedom of electric motors provides additional energy use reductions of a similar three times magnitude compared to helicopters (i.e. the ability to achieve a high Lift/Drag ratio by using a fixed wing VTOL approach along with synergistic aerodynamic integration benefits). This ten-fold decrease in vehicle energy use is critical for VTOLs to achieve a reasonable and sustainable transportation approach [Holden J., Goel N., 2016].

Visual pollution of the UAM

While VTOLs will be clearly visible during takeoff and landing, the impact that they will have on city skylines and in areas of natural beauty when flying at much higher altitudes between A and B is harder to imagine. Simulations can be produced to visually model different densities of VTOLs from the perspective of a person standing on the ground to determine any locally specific challenges. Visual pollution concerns can be addressed via trip route modifications to avoid particularly sensitive vistas or consolidating traffic to existing commute corridors such as above highways [Holden J., Goel N., 2016].

Conclusion to UAM

The expanding UAM vehicle industry has generated a significant level of enthusiasm amongst aviation designers, manufacturers and researchers. This industry is determined to change the urban transportation paradigm from traditional ground-based vehicles (cars, taxis, buses) to air-based UAM vehicles which can be summoned similar to conventional taxi services. These new UAM vehicles are designed to be small, lightweight and operate autonomously without user interaction.

There are many unknowns as to how the industry will mature. A critical challenge for UAM market growth is to gain public acceptance for being as safe as, or safer than, commercial air travel and automotive transportation. Crash avoidance technologies in autonomous systems are continuously in development. Despite these efforts, crashes will likely occur, and subsidiary crashworthy systems must be in place to mitigate the injurious loads. It is in this area of crash mitigation where much attention is needed.

Crashworthiness involves a system-level approach to account for all energy absorbing contributions from the landing gear/skids, airframe, seat, and restraints. Current landing gear struts on utility helicopters (the category most closely related to UAM) are primarily oleo-pneumatic and limit loads for a variety of sink rates. These legacy struts may be too heavy for UAM concepts, and simpler and more lightweight struts are required. Energy absorbing struts must withstand normal load profiles but activate in the event of a hard landing or crash. Concepts that have been studied to date for crew seats or landing gear include, but are not limited to, tubes with crushable cores, inversion tubes, wire benders, and tube crimpers.

The technology solutions proposed under this subtopic will address the need to demonstrate vehicle safety under a hard landing or crash condition for UAM aircraft. Examples of preliminary missions, requirements, and concepts for UAM aircraft can be found in references. It is conceivable that the capability of a Ballistic Recovery System would be negated if deployed at these proposed low altitudes. Vertical drop testing conducted at NASA Langley Research Center in 2018 has shown that from a height of only 14 ft, which generates an impact velocity of ~29 ft/s, occupant loading limits were exceeded for occupant protection specifications in both General Aviation and rotorcraft. While not directly comparable due to the unknowns in

UAM performance and regulations, these tests demonstrate that comparable impacts from even low levels have the capability of causing injury.The expected technology readiness level (TRL) range at completion of NASA projects is between 3-6.

The aerospace industry is characterized by low quantities and low economies of scale compared to the automotive industry with its cost-efficient mass production. The top-selling Airbus A320 was sold 417 times in 2018, which is less than a tenth of the sales volume a BMW 3 series has per week with 366,475 units in 2018.

Key components such as the propulsion system are flight critical and can lead to emergency situations, catastrophic events, and high liability claims. Therefore, such products must comply to the certification specifications defined by regulatory authorities such as the Federal Aviation Administration (FAA) of the United States of America or the European Aviation Safety Agency (EASA). The certification requires among others, extensive testing, validation, and related detailed documentation and reports. Furthermore, a certificate approving the manufacturing of the type certified product is required and all produced components must be highly traceable. These certification and compliance requirements lead to the high development and industrialization effort which needs to be allocated to the low quantities.

On the contrary, the automotive market is characterized by its high sales numbers and the high competition which demands for a cost-efficient mass production and lean organization and development processes. The effort for obtaining a type approval for a car is different to aviation, but the new eVTOL aircraft are also less complex compared to commercial civil aviation aircraft like the A320. Consequently, the capabilities of the automotive industry can help to reduce the costs, make air taxi fares more affordable for a broader public and can contribute to the expected market growth of the eVTOL industry.

At first, automotive players might perceive the requirements for certification as a high entry barrier. However, the supplier base for technologies, such as batteries and electric motors is less established compared to conventional aviation products. The profound experience automotive players already have from their products being used by end-customers on the road should not be underestimated since they provide real-world durability data. The acquired knowledge might help to establish a high level of confidence for respective authorities to certify products from new players. In addition, automotive players develop their products according to (automotive) ISO and SAE standards, which are similar to related standards of the aviation industry. Furthermore, the automotive industry is well experienced regarding supply chain, logistics, and production processes which will be required for a higher output compared to today's conventional aviation industry. Consequently, there might be a gap, but not a cold start to bring automotive products into the aviation market.

While certification of vehicles and integration into the airspace system will be challenging, there are additional barriers to consider. Public acceptance of advanced aerial mobility, particularly noise aspects and its psychological factors, is perhaps one of the biggest challenges along with safety. Failure to address these issues could hinder advanced aerial mobility implementation. Noise from aircraft and other transportation modes is a complex topic spanning acoustics, the physiological way humans experience noise, and the psychological perceptions listeners have of the source of the noise and what it represents to them.

Growing interest in UAM aircraft has been observed from different sectors, such as hobbyists, commercial entities, the military, government agencies, and scientists [Theodore CR. , 2018]. There is preliminary evidence that the public may be concerned with these new noise sources intended for transportation and package delivery [US Postal Service, Office of Inspector General, 2016]. Although there is only a very limited amount of research on subjective reaction to noise from these new aircraft types, indications that the noise characteristics differ from traditional aircraft warrant further research to understand and predict human perception of these sounds.

4.1.9. Electric aircraft

There have been consistent upward trends in the electrification of aircraft systems, research into Electrical Propulsion, and fundamentally, a greater investment of money and business effort into electric aircraft. Electrification not only offers the capability to reduce emissions, but could also unlock the potential for more energy-efficient aircraft and brand new architectures and use cases. Electrification could also revolutionise the supply base in the aerospace industry, posing an existential threat to incumbent suppliers and facilitating access for new entrants.

The conventional aircraft depends on four main power systems: hydraulics, pneumatics, mechanical and electrical power. Hydraulics is used for the majority of actuation functions. Pneumatics is associated with the system of pressurization, de-icing and air conditioning, whereas electrical power is used for avionics and utility functions. In the aerospace industry, electrification has manifested itself in two ways: the More Electric Aircraft (MEA) is an evolutionary trend in which each successive generation of aircraft has typically employed more electrical equipment in place of systems that would previously have been mechanical, hydraulic or pneumatic, and Electrical Propulsion, a potentially revolutionary new approach which has gained much recent publicity, and which, if adopted widely, would transform large segments of the aerospace industry, affecting not only propulsion, but also aircraft systems, and leading to radically new aircraft architectures. Many aircraft now employ electric systems, and/or a mix of hydraulic and electric systems (Figure 4.166).

However, to utilize the advantages of electrified systems, which include excellent efficiency and advanced functionality, the promotion of electrified aircraft system (MEA) and the promotion of electrified aircraft engine system in which hydraulic and mechanical pumps and actuators in the engine are electrified (MEE: More Electric Engine) have taken root as an effort directed towards safety, environmental friendliness, and cost effectiveness. Hydraulics is used for the majority of actuation functions. Pneumatics is associated with the system of pressurization, de-icing and air conditioning, whereas electrical power is used for avionics and utility functions. The electrical generating capacity of each successive generation of aircraft has increased, with the Boeing 787 and Lockheed Martin F-35 representing significant step changes (Figure 4.167). Indeed electrical loads of the Boeing 787 Dreamliner require almost 1000 kVA, a significant step when compared to the ~200 kVA of a more conventional Airbus A320. Taking into consideration the different number of maximum passengers onboard, a 72% increase in terms of power-per-passenger is registered (2.78 kVA-per-passenger for Boeing 787 and 1.61 kVA-per-passenger for Airbus A320).



Figure 4.166: Penetration of electrical systems by aircraft type

Another trend has been the switch from constant frequency generation derived from a constant speed gearbox and generator, to variable frequency generation with power electronics to convert the electrical output to the various frequencies and voltages required by different types of electrical equipment.

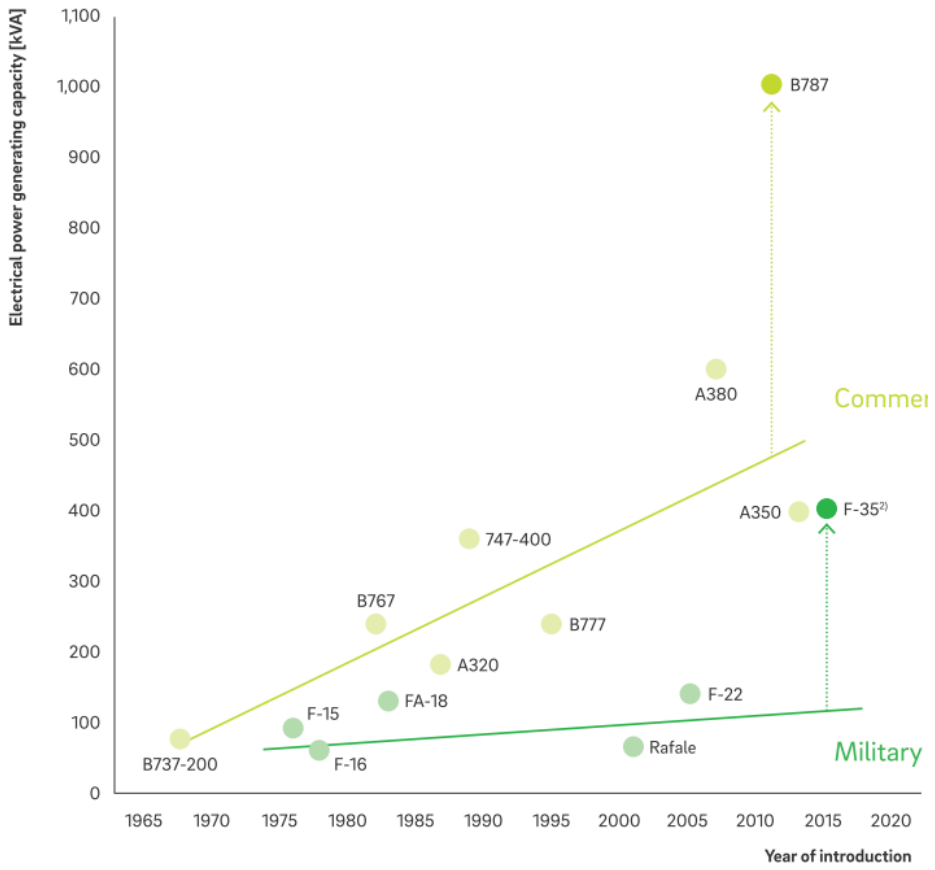


Figure 4.167: Electrical power generating capacity by introduction year [kVA]

The MEA assumes using on the aircraft board ample quantity of electric systems. Generally, such a solution increases the total electric energy consumption, but it allows decrease the onboard equipment weight. For example, the total hydraulic system can be replaced by several local hydraulic systems withelectric driven pumps providing required pressure.

Compared to the evolutionary MEA trend, Electrical Propulsion represents a radical change from today's propulsion technologies, although Electrical Propulsion is not without historical precedent.The development is carried out within the framework of the *DISPURSAL* project, according to the propulsive fuselage technology. In the advanced "more electric aircraft" will be used two diminished turbofan engines that will not only be responsible for the aircraft movement but also will generate electric power for energizing its onboard systems and the fan electromotor mounted in its aft body. The contribution of this engine in shaping the total thrust makes up 23 %.It is perceived that the MEA and, in the future, all-electric aircraft (AEA) technologies can decrease fuel consumption by 9%. Besides these benefits, it is also anticipated that MEA and AEA concepts will lead to an overall average weight cut by 10%[**Cao W., Mecrow B. C., Atkinson G.J., Bennett J. W., Atkinson D. J., 2012**].

In the comparative simulation involved was an aircraft designed under the DISPURSAL project, of 340 passenger capacity and a flying range of 8...9 thousand kilometres. It was compared with a modern Airbus passenger aircraft A330-300. During the simulation, the aeroplanes were carrying out flights at a velocity of M= 0.78 (963 km/h). The efficient performance of the new aeroplane in comparison with the A330-300 will make up 38.3 %.

A number of research organizations is studying system concepts oriented towards the research and development of the next stage of this technology: All-Electric Aircraft (AEA) systems that consolidate the component systems. Figure 4.168 illustrates the All-Electric Aircraft system.

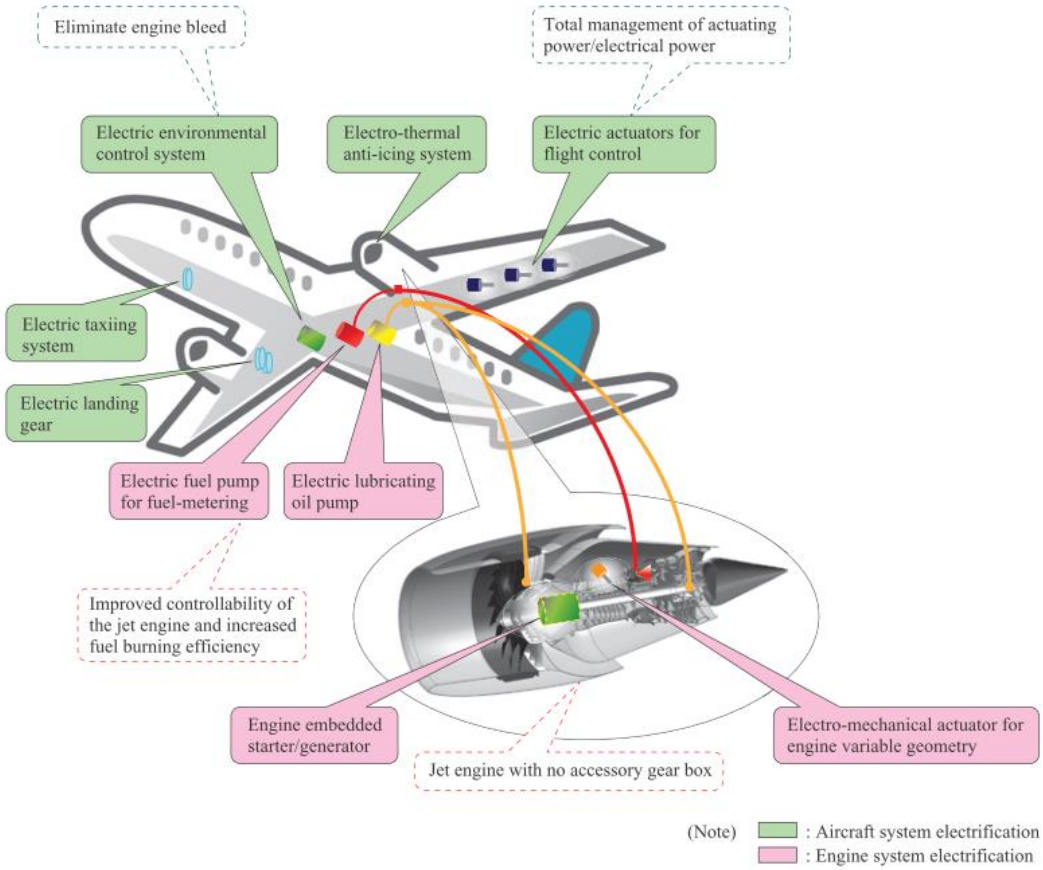


Figure 4.168: Overview of the All-Electric Aircraft system [Morioka N., Takeuchi M., Oyori H., 2014]

An overview of the research related to All-Electric Aircraft and engine systems, as well as the technological features and challenges thereof, have been discussed primarily in terms of advanced technology efforts indicated below [Morioka N., Takeuchi M., Oyori H., 2014]:

- Although the electrification of aircraft around the world today has mainly progressed by electrifying accessories, future challenges lie in propulsion, control, and power system integration. Integrated management of engine and electric power generation, regenerated power absorption by the engine, and integrated thrust flight control are the system concepts addressing these challenges.

- Realizing these system concepts will require new technology innovations. Regenerative Fuel Cell systems, electric fuel systems, aircraft power accumulators, and reliability improvements in electric actuators are examples of such crucial technology innovations, and their research and development is progressing.

- Electric Active Laminar Flow Control systems for contributing to further reductions in fuel consumption, and autonomous distributed air cooling systems for achieving serviceability improvements and reductions in substances of concern are also being considered.

The electrification of aircraft makes it possible to attain the global and societal demands for improved safety, environmental friendliness, and cost effectiveness, and holds promise as a next-generation aircraft system that will help to realize aircraft that are both people-friendly as well as environment-friendly. IHI is contributing its own technologies to the electrification of the world's aircraft, with a primary focus on engine electrification systems. Within the area of Electrical Propulsion, there are three broad aircraft architecture choices designers can make. There are three main architectures for Electrical Propulsion, Table 4.33.

The technical barriers to currently envisaged electrically-propelled aircraft can be grouped into two types: those that relate directly to the electrical system, and those that are linked to the planned applications of the aircraft

under development. High battery storage capacity and low weight are clearly crucialtoall-electricandhybrid-electricarchitectures, and in order to begin to allow the creation of products with commercially viable payload-range characteristics, it is generally accepted that electrical storage systems need an energy density of at least 500 Wh/kg. The highest commercial batteries today range from 150-250 Wh/kg, with Tesla's 21-70 battery having a reported energy density of 250-320Wh/kg.In addition to highenergy density, high re-charging speeds and long battery life-cycles will be crucial to underpinning the economics of battery-powered aircraft.

Hybrid-electric: Hybrid-electric is one of two architectures – Parallel or Series hybrid. Additionalelectric energy can be used for acceleration and in times of high power demand, and bi-directional flow of power is possible between the generator and battery.

Turbo-electric: The kinetic energy of a turbo shaft is transformed into electric energy via a generator to drive multiple, distributed fans, with the fans driven by electric motors.

All electric: One, or multiple, fans are driven by electric motors with energy stored in a battery.

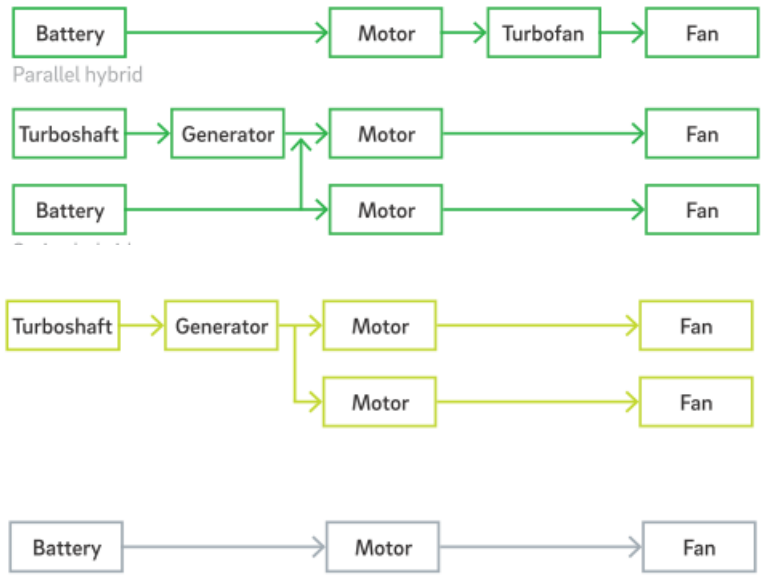


Table 4.33: Electrical propulsion architectures

Stepwise development to meet environmental targets in aviation sector – evolutionary and revolutionary technology solutions to be researched and implemented – provides a necessity to formulate midterm and long term goals, especially driven by climate change impact of aviation. For example a concept of More Electric Aircraft (MEA) covers a number of technologies to be introduced in aircraft control in flight during nearest decades (midterm goals for emission reduction and energy supply). Full Electric Aircraft (EA) concept is considered like a subject of deep concern for the last decade (long term goals) in progress to 2050 achievements. Complexity of the Challenge 3 towards *FlightPath 2050* creates the conditions when/where new evolutionary and revolutionary technology achievements are expected in all spheres of aviation sector – aircraft design and manufacturing, their operation and maintenance, including airport and ATC infrastructure and procedures.

This will include the benefits of changes to technology embedded onto aircraft, including the coming revolution in full-electric (use batteries and generators as the only power source on the aircraft, including for the propulsion) or hybrid electric power for aircraft and other offenders like the possibilities of urban air mobility vehicles. In this way an electrification of the aircraft has the potential to revolutionize the aviation industry as a whole, providing its less impact on environment.

Electric and hybrid-electric propulsion is rapidly revolutionizing mobility technologies across industries, from automotive to marine. And the aviation industry is no exception (Figure 4.169). Airbus is committed to developing, building and testing electric and hybrid-electric future technology that will enable the aviation industry to significantly reduce the CO_2 emissions of commercial aircraft.

Up to date a number of new programmes were launched globally for the four groups of the aircraft – General Aviation/Recreational Aircraft (GA), Urban Air Taxis (UAT, aircraft with vertical take-off and landing - VTOL), Regional/Business Aircraft (RA/BA) and Large Commercial Aircraft (LCA). All of them are the starting points in existing roadmap for electrification of the aircraft, as shown in Figure 4.170, most of them are planned to

entry in service in nearest decade 2020-2030, but some of them are already commercially available even now. The first flights of RA/BA prototypes for 9 - 12 passengers are planned during 2019-2020, with their type certification in between 2020-2022.

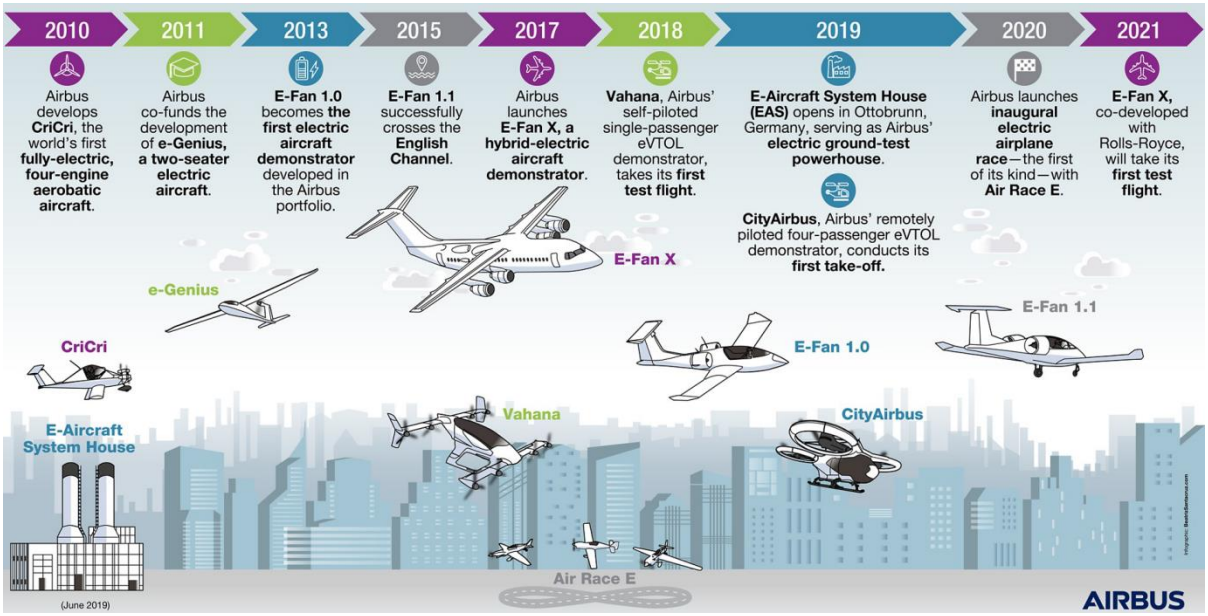


Figure 4.169: A timeline of achievement in electric propulsion[https://www.airbus.com/innovation/future-technology/electric-flight.html]

In parallel a creation of regional electric network must begin between the airports located on flight distance close to 1000 km between themselves. LCA includes mainly the attempts of Airbus in cooperation with Rolls-Royce and Siemens focused on the development of hybrid-electric, single-aisle aircraft - their jointly produced demonstrator E-Fan X is planned to fly at 2020. In nearest plans of the biggest EU low-coster Airline EasyJet is to implement these aircraft within the next decade. UAT/VTOL aircraft also have made significant progress over past years. For example, Chinese and German (but NASA, Bell Helicopters and Embraer contributed into development and design) electric UAT/VTOL has been tested during 2017-2018, so final commercial product may fly into the market even within a year-two.

Airbus has joined together the efforts with Rolls-Royce and Siemens for developing a flying demonstrator dubbed E-Fan X (Figure 4.171) that will broaden significantly the application of electric motors on the commercial aircraft. The E-Fan X aeroplane is a flying demonstrator on the scale of suburban distances (Figure 4.172).

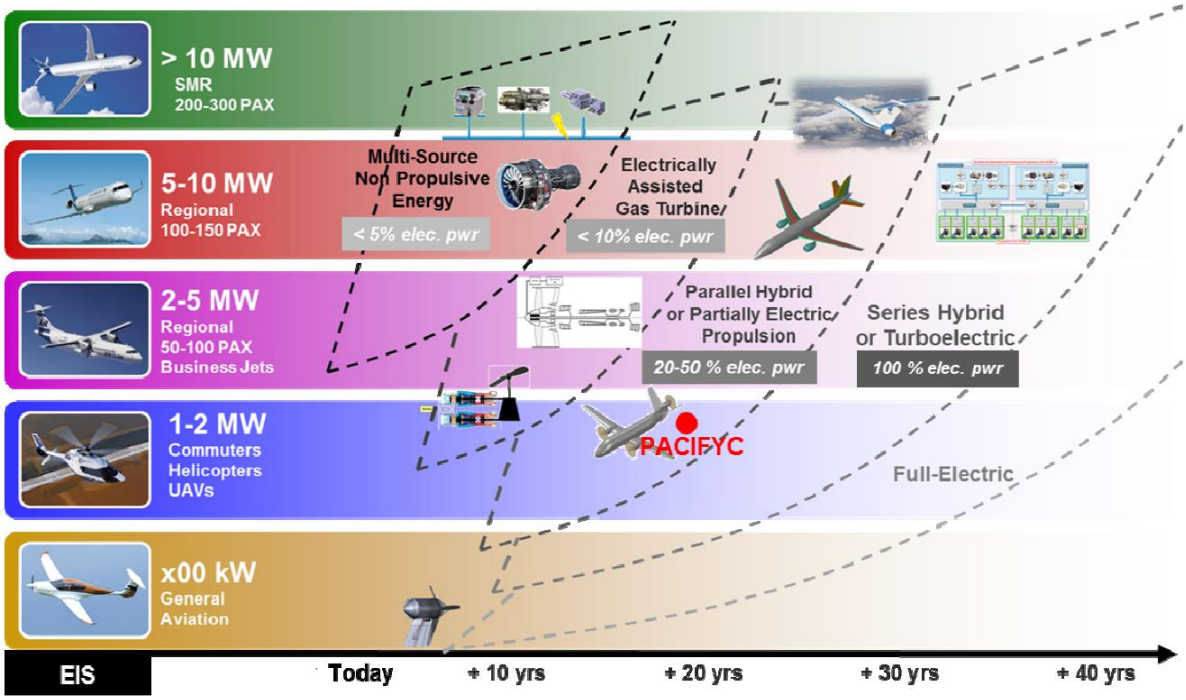


Figure 4.170: Trends of possible aircraft hybrid architectures at different installed power, from [Isikveren, 2016].

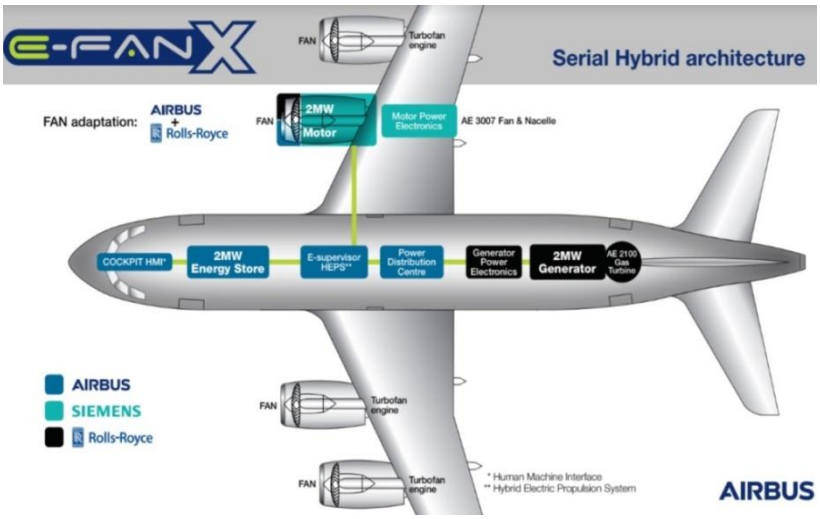


Figure 4.171: The plans of Airbus for creating an electric aeroplane



Figure 4.172: Project of E-Fan X

The flying demonstrator E-Fan X on the scale of a suburban jet aeroplane comprises one electric motor that is energized by the turbo generator embedded into the fuselage. Realized, is a consequential, hybrid architecture of the aircraft. The power value of about 2 MW was selected because this is the upper limit

available from the traditional technologies of electrical energy distribution, without the need of evolving the superconductivity or any other exotic approaches.

Integrative risks exist, such as thermal control, electro-magnetic interference effect, arcing, partial discharge and radiation exposure onto powerful electrical systems at altitude. The final objective is the creation of a hybrid-electric propulsion system for narrow-bodied aircraft at scales of A320 family and larger (Figure 4.170).

E-Fan X, the successor to E-Fan that is 30 times more powerful than its predecessor, is expected to take its first flight in 2021. E-Fan was powered solely by lithium-ion batteries and became one of the first all-electric aircraft to successfully cross the English Channel in July 2015. It also paved the way for the next generation of electric-powered and zero-emission aircraft technology at Airbus (Figure 4.172). For Airbus, a main goal is to make the technology available to fly a 100-passenger aircraft based on electric and hybrid-electric technology within the 2030s timeframe.

For the *E-Fan X,* the test programme has offered invaluable insight into the hybrid-electric demonstrator's aerodynamic design, low-speed performance and handling qualities in preparation for its first flight in 2021. For the *E-Fan X,* the test programme has offered invaluable insight into the hybrid-electric demonstrator's aerodynamic design, low-speed performance and handling qualities in preparation for its first flight in 2021. The BAe 146 RJ100 aircraft was not designed to have hybrid-electric systems on board. A scale model of a BAe 146 RJ100—a short-haul regional airliner originally designed in the 1980s—is being attached to the Filton wind tunnel in preparation for testing (Figure 4.173). In fact, it is the same wind tunnel model used in the certification of the original BAe 146 RJ100 aircraft. But this test model is not exactly like the original, the test programme offered insight on all aspects relating to low-speed performance and handling qualities. The test programme is conducted to modify the porosity of some of the devices inside the ducts to ensure they relate correctly to the full-scale E-Fan X model devices. Future milestones include flight tests for characterisation and installation of the 2MW motor on the test aircraft in 2020.



Figure 4.173: E-Fan X wind tunnel testing

In power plant there was involved creating a hybrid-electric power generation system at a scale never previously seen in our industry, comprised of an embedded AE2100 gas turbine driving a 2.5MW generator and 3000V power electronics and an electric propulsion unit. That's enough power to supply 2,500 homes and fully represents the pioneering spirit on this project.

Over the past three years, each successful *E-Fan X* milestone has offered us rich insights for the future, including:

- *Serial hybrid-electric propulsion*: Hybrid architectures, high-voltage systems and batteries are indispensable technology bricks for several other demonstrator projects across our wider R&T portfolio to diversify power sources. We will continue to develop and mature them at an E-Aircraft System Test House [https://www.airbus.com/newsroom/news/en/2019/10/new-airbus-facility-will-help-zero-emission-technologies-to-take-flight.html].

- *New pathways for disruptive CO_2 reduction*: Exploring the possibilities—and limitations of—serial hybrid-electric propulsion also opened up inquiry into new technology pathways. Hydrogen being one of them, which is equal parts a huge opportunity as it is a new challenge.

- *Future certification and regulatory acceptance*: From the start, we have been consistently delighted by our customers'—and indeed, the entire aviation ecosystem's—overwhelming enthusiasm for E-Fan X. With our research partnerships on hybrid-electric and hydrogen airport infrastructure and operations, we will have laid a foundation for the future industry-wide adoption and regulatory acceptance of alternative-propulsion commercial aircraft.

Thanks to these key learnings, Airbus has developed a more focused roadmap on how to progress on our ambitious decarbonisation commitments. A lofty achievement for a first-of-its-kind demonstrator like E-Fan X. It's through cross-industry partnerships like these that the aviation industry will bring competitive zero-emission solutions to the future of flight. Although E-Fan X will not take to the skies, I strongly believe that its spirit will live on as we continue on our journey towards climate-neutral flight.

Safran is a pioneer in the trend towards "more electric" aircraft, and one of the most innovative players in the industry (Figure 4.174). It already supplies a wide range of electric systems to replace conventional pneumatic and hydraulic systems, including deicing, flight control actuators, thrust reversers and brakes. The aim is of course to electrify aircraft systems, which in turn simplifies the overall energy system, facilitates maintenance and enhances control.

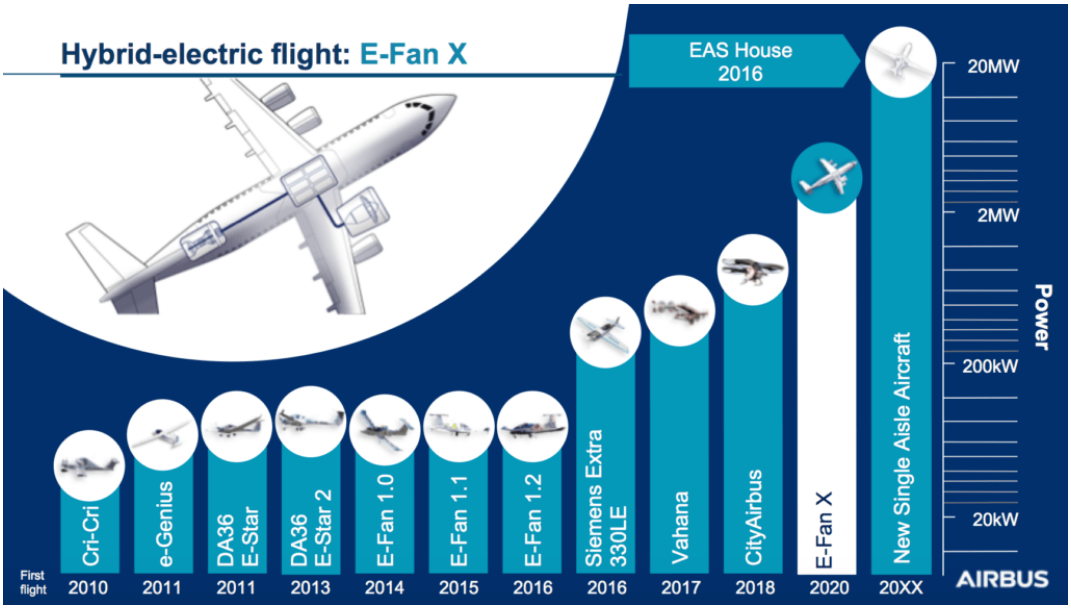


Figure 4.174: The plans of Airbus for creating an electric aeroplane

Safran will continue to devise innovative solutions for these strategic technologies and support a smooth transition to even more-electric aeroplanes and helicopters. From Safran the actual timetable for the entry into service of electric aircraft depends on multiple factors. Safran is planning ahead for these long-term step changes in the market, starting with shorter-range and more limited solutions, while awaiting technologies that are mature enough to store and deliver the electrical power needed for propulsion, Figure 4.175.

Electrical propulsion is finally on the map: almost 100 electrically propelled aircraft are already in development globally. Most developments are currently working on general aviation or urban air taxi architectures. Given the current state of technological advancement, this is unsurprising as these smaller architectures require less total power and are less limited by constraints such as battery and motor gravimetric densities.

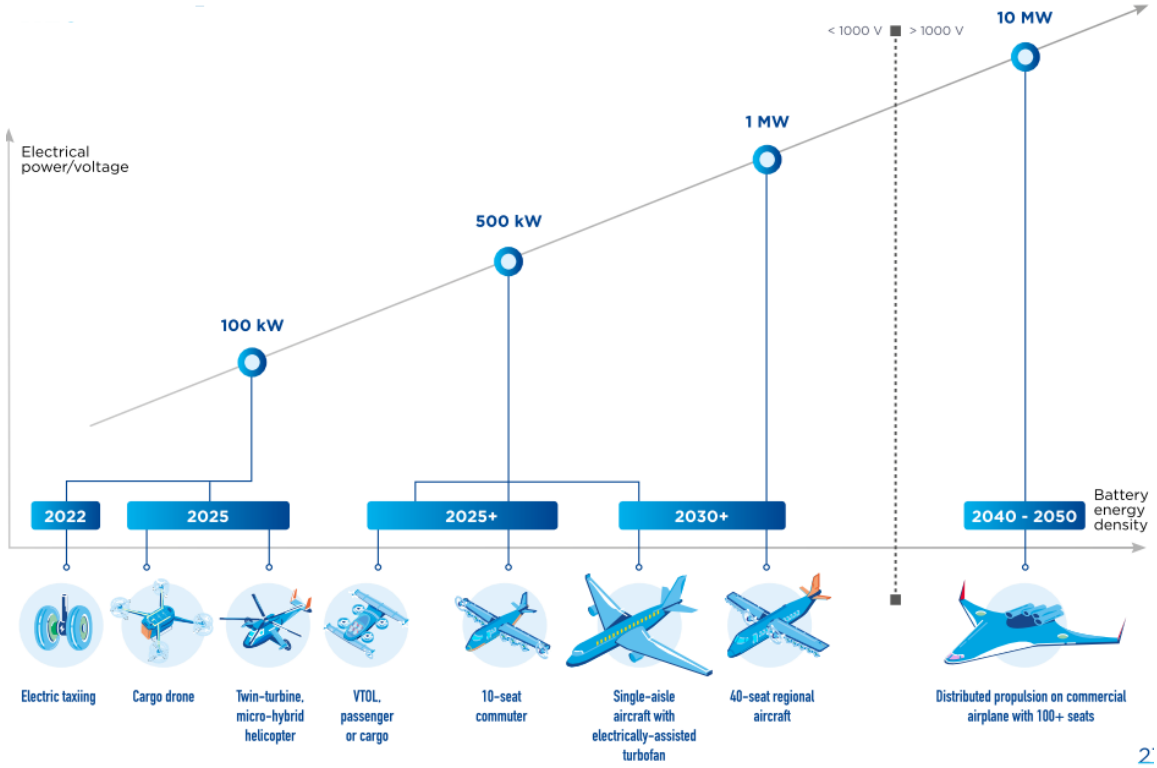


Figure 4.175: Roadmap for more and all-electric aircraft in view of Safran

Airbus has made significant progress in the electrification of flight, its all-electric, twin propeller aircraft *E-Fan* successfully crossed the English Channel in 2015. *Vahana*, a single-seat self-piloted all-electric vertical take-off and landing (eVTOL) tilt-wing vehicle demonstrator, has been flight testing since 2018, Figure 4.176. It is less noise in comparison with helicopter, it may achieve both vertical take-off and landing as well as cross-city flight range on battery power alone. Its cruise speed is 100 knots (190 km/h), enabling trip times that are two to four times faster than cars. *Vahana* is enabled by its onboard detect-and-avoid systems that can identify both air and ground hazards.

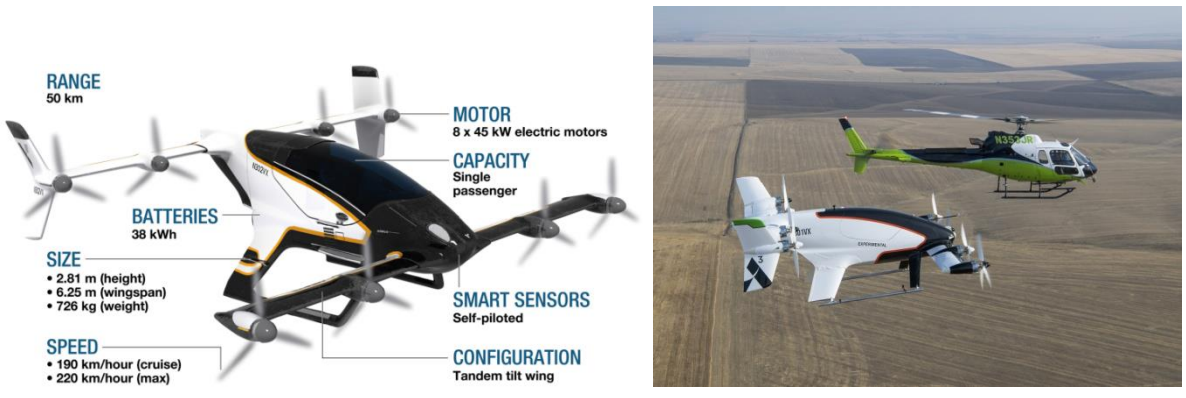


Figure 4.176: *Vahana* technical specifications

The *Vahana* programme was launched to cover three main objectives [https://www.airbus.com/newsroom/stories/Vahana-has-come-to-an-end.html]:

- *Designing a fully operational eVTOL vehicle*: A sketch on a napkin is one thing, but proving the technical viability of the configuration is quite another. The project team pushed its idea of a tilt-wing configuration with a suitable battery-to-electric-motor solution to the limits. When *Vahana* took its first flight in 2018, t*he leap from concept to reality was a success*.
- *Proving the viability of self-piloting technologies*: Vahana was launched at a time when real-time detect-and-avoid capabilities on small aircraft were considered a pipedream. Today, *Vahana* is fully capable of autonomously detecting airborne and ground hazards. The project was thus instrumental in helping to de-risk core elements of autonomy for urban air mobility vehicles and gave rise to Wayfinder, an ambitious autonomous flight technology project at Acubed.
- *Developing an eVTOL business case*: What is the total operating cost of eVTOLs? How does it compare to traditional helicopters or taxis? What is the value for the community? How should they be certified? All of these questions need to be ironed out to create a compelling business case. And *Vahana* offers rich learnings in this respect.

CityAirbus, an eVTOL demonstrator from Airbus again, with a four-passenger capacity, successfully conducted its first take-off in May 2019, Figure 4.177. *CityAirbus* has a multicopter configuration that features four ducted high-lift propulsion units. Its eight propellers are driven by electric motors at around 950 rpm to ensure a low acoustic footprint. The single failure tolerant architecture ensures safety. Its cruise speed will be approximately 120 km/h on fixed routes with up to 15 minutes of autonomy. It has a capacity of four passengers that is ideal for aerial urban ridesharing. Among of its advantages are the following: remotely piloted with advanced control systems, less noisy than traditional helicopter, 3x faster than cars.

At present activities are extensively carried out on using distributed propulsion systems, with the energy from the turbine being transferred to the fan propellers either via mechanical transmission or in the form of electrical energy. In the latter case, the drive of the fan propellers is carried out using an electric motor. Expected reduction of specific fuel consumption at cruising rating (M= 0.8, H= 11 km) for this type of propulsion systems in comparison with the modern turbofan engines is estimated approximately in 15 % [*United area of innovations:* http://mrgr.org/docs/detail.php?ID=507].



Figure 4.177: *CityAirbus* technical specifications

Both of Airbus eVTOL demonstrators are undergoing a rigorous and comprehensive flight test programme to ensure safety and high performance. Zach Lovering, VP of UAM Systems, Airbus: Learnings from both aircraft—Vahana and CityAirbus—will be used to advance our relationship with regulators and to understand key technologies [https://www.airbus.com/newsroom/stories/Vahana-has-come-to-an-end.html]. Although precise timelines for the future vehicle are still to be determined, work on the new design has already begun. Airbus Urban Mobility program (Chapter 4.4) is tasked with taking the lead on this front.

Apart from the reduction of specific fuel consumption the possibility for suction of the boundary layer is being worked out, via the fans driven by the electric motors of the distributed propulsion systems (Figure 4.178).



Figure 4.178: Projects of aeroplanes with distributed propulsion systems and boundary layer suction

Thus, in short-term and mid-term prospects predominance of the turbofan bypass engines on heavy transport systems will be maintained, Figure 4.179. The improvement development of the propulsion systems will be directed, at first instance, on increasing the efficient performance both of the engine itself (at the expense of increasing the bypass ratio, elevation of gas temperature, compression ratio and soon) and of the aircraft in whole (use of conceptions “more electrical” aircraft, distributed propulsion systems, boundary layer suction, and so on).

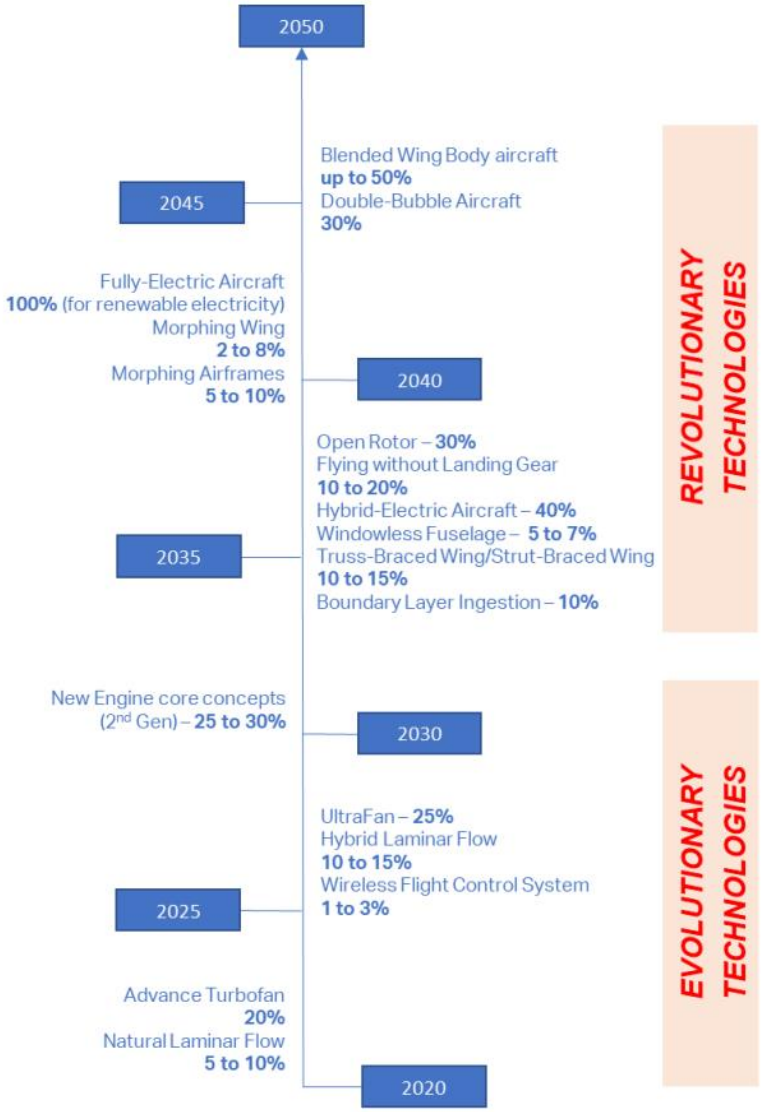


Figure 4.179: Timeline of expected future fuel efficiency improvements compared to predecessor aircraft or engine of the same category

An example of an operational goal supporting the implementation of new aircraft technologies relates to the plans of electrifying aviation in Norway. Avinor, the public operator of most Norwegian airports, in conjunction with the Norwegian government, aims at operating all short-haul flights (up to 90 minutes on domestic routes and those to neighboring Scandinavian airports) with electric aircraft by 2040 [Avinor, 2018].

The most important parameters for aircraft systems are specific energy (Wh/kg) for energy storage and specific power (kW/kg) for electrical components (Table 4.33). 500 Wh/kg is widely regarded capacity of the batteries as a minimum required for electric flight with commercially acceptable payload-range characteristics. Projected roadmaps indicate the batteries will only reach the 500 Wh/kg level only after 2025 (N+3). So, the most interesting now group of aircraft – single-aisle LCA and RA (PAX capacity over 100) will be started for designing and testing close to 2040, thus to expect for their essential contribution to solve the strategic task provided by neutral carbon growth scenario. Wright Electric has announced its intention to build a 150-seat electrically-propelled aircraft (expected full-electric, if batteries will be available, otherwise – of hybrid-electric architecture) within a decade to compete with the smaller members of the Airbus-320 and Boeing-737 families [Berger R., 2018]. So, new technologies for high specific energy batteries are looking dramatically important as for revolutionary new all-electric architectures, so as for successful solution of more strategic task – to satisfy the declaration of 1,5-2,0°C budget for global temperature through 2050,

which is mostly looking to be covered in aviation sector by SAFs. Despite the losses in converting the energy contained in jet fuel into useful thrust, the energy density advantage of jet fuel remains a factor of 6-8 times higher than the 500 Wh/kg batteries.

	Electric system performances		Battery capacity
Aircraft type	Power Capability, MW	Specific Power, kW/kg	Specific Energy, Wh/kg
GA and commuters:			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator <1	>6.5	Not applicable
RA and single-aisle LCA:			
Parallel hybrid	Motor 1…6	>3	>800
All-electric	Motor 1…11	>6.5	>1800
Turboelectric	Motor 1.5…3, generator 1…11	>6.5	Not applicable
Twin-aisle:			
Parallel hybrid	Still not studied		
All-electric	Not feasible yet		
Turboelectric	Motor 4, generator 30	>10	Not applicable
APU for large aircraft	Generator 0.5…1	>3	Still not studied

Table 4.34: Electric systems and battery requirements for electric aircraft architectures (modified from [NAP Report 23490, 2016])

Turboelectric concepts are not dependent on advances in energy storage technologies. Turboelectric propulsion systems are likely the only approach for developing electric propulsion systems for a single-aisle LCA PAX that is feasible in the considered time frame – till 2050. A partial turboelectric architecture (or some other variant of a turboelectric system) is likely to provide the first opportunity for an electric propulsion system to be incorporated in a regional or single-aisle aircraft configuration and is the first application likely to begin having a significant impact on reducing aviation carbon.

Considering a time span up to 2035, correspondent to +20 years in Figure 4.180, one can see how full electric power is expected to be employed only in GA and in some UAT/VTOL applications, while partially electric propulsion would be needed to power UAT and RA propeller-driven aeroplanes. Turbofan aircraft would at most benefit from assisted electric power, provided that a trade-off could be made between engine mass increase and fuel consumption, noise and pollutant emissions decrease; only MEA tendency is thus expected. Taking in mind the contribution of BA, RA and turboprops in total fuel consumption (Figure 4.170) it is looking obviously not enough to concentrate on electrification of these groups only.

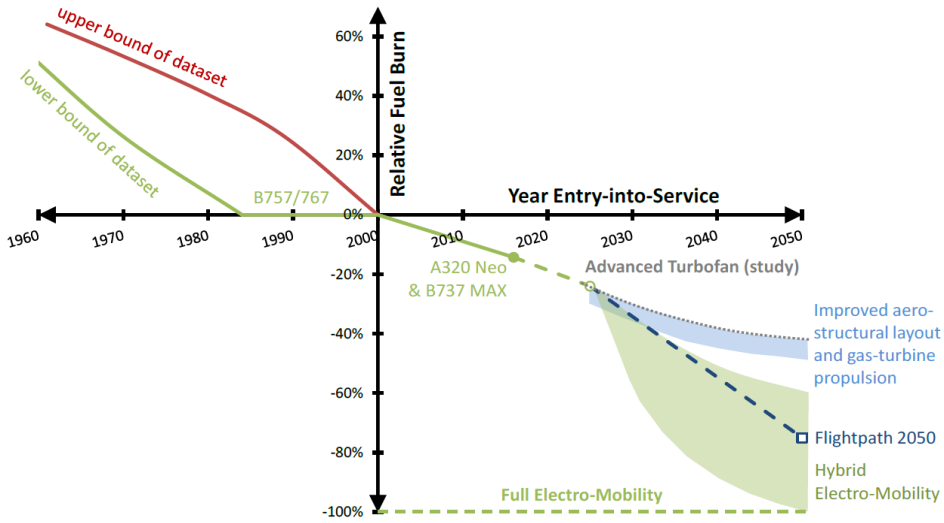


Figure 4.180: Fuel burn reduction expectation with respect to year 2000 [Isikveren A.T., Sizmann A., Hornung M., 2011]

Moving to a larger time span, up to 2050 (+35 years in Figure 4.180) heavy uncertainty and requires large improvements in terms of power-to-weight ratio of electric motors and electro-mechanical conversion, cooling systems, wiring and, of course, on batteries. Taking year 2000 as a reference, as considered by Flightpath 2050 program, it can be expected an improvement due to hybrid electro-mobility starting around 2025, with fuel saving around 25-30% per flight due to advanced turbofan studies, while further improvements are subjected to really large uncertainties.

Aviation has always been a high-tech industry, and continuous progress in the development of new technologies is vital for a sustainable growth of the aviation industry. They are not only the basis for a more fuel-efficient fleet, but also a key factor for improvements in flight and ground operations, for a pleasant passenger experience and for reducing as much as possible the impacts of air transport growth on the environment.

The electrification of air transportation is considered currently as one of evident consequences among the technological consensus solutions to reduce in fossil fuel consumption in aviation sector, which also means the reduced emissions: as in terms of GHG, so as for usual LAQ emission inside airport area – NO_x, CO, HC and PM. The use of power from onboard batteries eliminates the aircraft operational emissions for all-electric architectures and reduces emission from hybrid electric ones. Existing potential and forecasted progress for MEA concept is showing quite limited reduction in fuel burn and emission. EP may provide essential reduction, but in considered time frame it is looking to be very possible for implementation in groups of General Aviation/Recreational Aircraft, Urban Air Taxis (first of all with vertical take-off and landing) and Regional/Business Aircraft first of all. More than 90 % of GHG emissions from global commercial aircraft operations are generated by Large Commercial Aircraft (twin-aisle and single-aisle aeroplanes with more than100 passengers), so research to reduce commercial aircraft emissions will be most useful if it focuses on technology applicable to these LCA. But for this group the uncertainties in reaching the effective values in specific energy for energy storage and specific power for electrical components are looking huge, TRL for them is quite small currently. Wright Electric has announced its intention to build a 150-seat electrically-propelled aircraft (expected full-electric, if batteries will be available, otherwise – of hybrid-electric architecture) within a decade to compete with the smaller members of the Airbus-320 and Boeing-737 families [BergerR., 2018]. So the gap between the evident scenario of technology/operational improvements for the aircraft with evolutionary architectures and neutral carbon growth scenario, which is required by 1,5-2,0°C budget for global temperature through 2050, is mostly looking to be covered by SAFs. Since SAFs is a global issue, not linked solely to aviation, but also to other types of transport and economical sectors (competition with other sectors for biomass will be expected), strengthening the partnership between the

aviation and energy sectors will be necessary. The technical feasibility of SAFs usage in aviation was proven and commercial aviation has already sent a number of strong signals that should the quantities of biofuels needed for the industry be produced sustainably, at right place, with concurrent price, there would definitely be a strong demand for these fuels.

Operational measures are among the elements in the basket of measures available to States to address the impact of aviation on the environment. Improved operational measures have the potential to reduce fuel consumption, and in turn, CO_2 emissions. For every tonne of fuel reduced, an equivalent amount of 3.16t of CO_2 are avoided. CAEP has developed updated guidance material to replace [ICAO Circular 303, 2004]. This was done to provide it to States and other stakeholders.

For example, the aircraft designed for (a) high cruise efficiency and low global emissions and (b) low noise and emissions at take-off and landing near airports may be quite different. The objective (b) leads to a glider like an aircraft with wide span wing and engine with a slow cold exhaust, for the low engine and aerodynamic noise and reduced emissions; this configuration has a low cruise speed and poor efficiency leading to longer travel times and higher fuel consumption and emissions in cruise flight. Conversely, the objective (a) leads to an aircraft with sweptback wings and high jet exhaust velocities for fast cruise and low fuel consumption and emissions that will be noisier and have more emissions near airports because of higher speeds and exhaust velocities at take-off and landing.

The multitude of engine and noise sources and the compatibility of low CO_2 and NO_x emissions at local and global levels are a formidable set of environmental constraints and objectives that may require major breakthroughs such as: (i) variable cycle engines with high jet speeds at cruise and lower exhaust velocities at take-off and landing; (ii) novel aircraft configurations like flying wings, joined wings, V- or U-tails with shielding of noise and/or flush or buried engines. These developments that may be needed to meet (a) ever-stricter environmental standards must be compatible with (b) increased efficiency and economy since both enable the continuation of air traffic growth at the service of mobility.

In 2008, the EU decided to include aviation activities in the EU ETS [**EC, 2008, Directive 2008/101/EC**]. These emissions now form part of the EU's internal 20% greenhouse gas (GHG) emission reduction target for 2020. Based on national GHG emission reports to the United Nations Framework Convention on Climate Change, domestic aviation from the EU Member States accounts for less than 0.5% of total EU GHG emissions, whereas international aviation represents 3%, a relative share which is increasing [**EEA, 2014**]. One example is the ETS which is a cornerstone of the EU's policy to combat climate change and its key tool for reducing industrial greenhouse gas emissions cost-effectively. The ETS either incentivises CO_2 emission reductions within the sector or through the purchase of emission reductions in other sectors of the economy where abatement costs can be lower.

In addition to improving operational efficiency and achieving technological progress, the aviation community is putting significant efforts in promoting the use of sustainable alternative fuels that have a reduced carbon footprint compared to conventional jet fuel. However, hurdles (mainly economic) still exist to prevent a large-scale production. A complementary global MBM scheme would act as a policy tool that would allow for an immediate response to the need for cost-effectively stabilising the emissions for international aviation to meet its aspirational goal.

According to Assembly Resolution A39-3, paragraph 4, the role of a global MBM scheme is to complement a broader basket of measures to achieve the global aspirational goal (of carbon-neutral growth from 2020 onwards). Paragraph 5 of the Assembly Resolution decides to implement a global MBM scheme in the form of the Carbon Offsetting and Reduction Scheme for International Aviation (*CORSIA*) to address any annual increase in total CO_2 emissions from international civil aviation (i.e. civil aviation flights that depart in one country and arrive in a different country) above the 2020 levels, taking into account special circumstances and respective capabilities. The average level of CO_2 emissions from international aviation covered by the

scheme between 2019 and 2020 represents the basis for carbon-neutral growth from 2020, against which emissions in future years are compared. In any year from 2021 when international aviation CO_2 emissions covered by the scheme exceed the average baseline emissions of 2019 and 2020, this difference represents the sector's offsetting requirements for that year.

As in paragraph 9 of the Assembly Resolution, the CORSIA is implemented in phases, starting with the participation of States voluntarily, followed by participation of all States except the States exempted from offsetting requirements, as follows:

- Pilot phase (from 2021 through 2023) and first phase (from 2024 through 2026) would apply to States that have volunteered to participate in the scheme; and
- Second phase (from 2027 through 2035) would apply to all States that have an individual share of international aviation activities in RTKs in the year 2018 above 0.5 per cent of total RTKs or whose cumulative share in the list of States from the highest to the lowest amount of RTKs reaches 90 per cent of total RTKs, except Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs) unless they volunteer to participate in this phase.

States that voluntarily decide to participate the CORSIA may join the scheme from the beginning of a given year and should notify ICAO of their decision to join by June 30 the preceding year. CORSIA would be the first global MBM scheme for a whole sector and a major step to complement the efforts made by States in the context of the Paris Agreement. Action for the implementation of the global MBM scheme for international aviation from 2020 will start right after the Assembly.

The major environmental issues of aviation concern noise and emissions (Key Topic T4.1) that are the subject of different views in the literature (Key Topic T4.2). The prospect of emissions-free airport movements is related to battery technology (Key Topic T4.3).

The long-term sustainability of aviation may depend on the availability of alternative fuels (Key Topic T4.4).The atmospheric research contributes to minimising the weather and environmental effects of aviation (Key Topic T4.5).

KEY TOPIC T4.1 – REDUCTION OF NOISE AND EMISSIONS

Benchmarks

As a result of technological improvements, the noise footprint of new aircraft is at least 15% smaller than that of the aircraft they replace.

According to ICAO, aircraft being produced today are 75% quieter than those manufactured 50 years ago. In spite of technological and operational advances, many airports have responded to community pressure by introducing noise-related charges on aircraft. However, the introduction of noise-related charges is often not an effective means to reduce the exposure of local communities to airport noise. Noise-related charges do not drive the development of quieter aircraft nor their deployment to airports. Additionally, noise-related charges are often introduced without a proper airport noise management plan and are often based on criteria that are inconsistent across airports and lack transparency. Funds generated by such charges are also not always dedicated to noise alleviation and prevention measures. Furthermore, the additional financial burden they put on airlines and passengers has a negative impact on the local economy.

In 2001, the ICAO Assembly unanimously endorsed the ICAO Balanced Approach to Aircraft Noise Management by adopting Resolution A33-7. The core principle of the Balanced Approach is that the noise situation at each airport is unique and that there is no one-size-fits-all solution. The ICAO Balanced Approach,

therefore, requires that all available options be evaluated to identify the most suitable measure or combination of measures to mitigate a specific noise problem.

NEW ENGINE ARCHITECTURES

Preliminary studies to probe various technologies have already been conducted, or are being conducted, both for Ultra High Bypass Ratio engines and Open Rotors. These two technological tracks are both presumed to lower fuel consumption and to reduce noise emission (at least jet noise, since tonal noise, may dramatically increase for Open Rotors).

For instance, from 2008 to 2011, within the DREAM project (EC 7 framework program), preliminary campaigns were led to compare noise measurements and numerical simulations on some Open Rotor configurations. Computational Fluid Dynamic (CFD) and Computational AeroAcoustics (CAA) made by Onera (France) appeared to be in good agreement with the measurements performed by Tsagi (Russia).

Progress up-to-now/ Predictions up-to-2025/ Evolutionary progress up-to-2025

In 2014, ICAO adopted a new standard that will result in a reduction of 7 Effective Perceived Noise Decibels (EPNdB) compared to the current Chapter 4 Standard. The new standard will apply from 2018.

As a result of technological improvements, the noise footprint (85 dB(A) maximum sound pressure level contour) of new aircraft is up to 50% smaller than that of the aircraft they replace (Source: Lufthansa). Further design improvements such as blended wing body and engine shielding by fuselage and tailplane offer the potential to reduce perceived noise from aircraft by 65% by 2050 (Source: Sustainable Aviation). Airlines will be investing USD 4.5 trillion in newer and quieter aircraft over the next 20 years (Source: IATA). CAEP IEP2 report established the goals for four classes or categories of aircraft were as follows (Table 4.15).

The use of measured static engine test noise data or pseudo-random noise signals with spectral shape and tonal content representative of **turbofan engines** is an acceptable alternative to the use of actual flight test noise data samples for determination of analysis system compatibility. The systems can be considered to be compatible if the resulting differences are no greater than 0.5 PNdB for an integration time of 32 seconds.

NEW ENGINE ARCHITECTURES

Beyond these local improvements, some attempts have been made to experiment far more dramatic modifications of the engine architectures.

Extensions of works made from 2008 to 2011, within the DREAM project (EC 7 framework program) are now conducted within the CleanSky Framework: In France for instance, Snecma's Hera test vehicle underwent preliminary testing in Onera's S1 wind tunnel in July 2013. Full-scale propeller tests were made in 2015.

Further new technological research programs have already been launched. Especially, it is worth mentioning COBRA, a new EU-Russia cooperation program that started in October 2013 and that is considered as the continuation of VITAL and DREAM. Actually, COBRA is dedicated to the consolidation of Ultra High Bypass Ration (UHBR) Contra-Rotating TurboFan (CRTF) that was once explored by Kuznetsov – one of the Russian partners – in the early 90s and further explored within VITAL. CRTFs associate two contra-rotating fans in a nacelle and thus appear as a kind of hybrid between turbofans and Open Rotors. CRTFs envisaged by COBRA strongly differ from those experimented with within the VITAL program and by the Russian engine manufacturer. Kuznetsov's NK-93 (BPR ~ 16.5) highlight the good behaviour in term of performance of this concept, but the design was made over more than 20 years ago without the current computational tools and free from present environmental constraints.

At the time being, indeed the first NK-93 full-scale tests showed that noise performances of such UHBR CRTFs were not so bad and that the combustion chamber has been up to now one of the most efficient among the Russian ones. Compared to VITAL, COBRA plans to explore a higher bypass ratio (BPR ~ 11 within VITAL) with the obligation to use a gearbox in order to reduce the fan speed. This reduction will directly impact the tip velocity and thus will allow the fan noise to be reduced. Within the COBRA project, the BPR investigated is from 15 to 25, according to the detailed specifications proposed by the partners in charge of this activity (Snecma and Kuznetsov).

A specific conception/optimization will be proposed by European research centres (Onera and DLR) and by Russian partners (CIAM, Kuznetsov, AEROSILA and MIPT). Both designs will be manufactured by COMOTI and tested at CIAM's C3-A test rig facility.

NASA/P&W Ultra High Bypass Turbofan Research

Under the Engine Validation of Noise and Emissions Reduction Technologies (EVNERT) task of the NASA Glenn Revolutionary Aero Space Engine Research (RASER) contract, which was sponsored by the NASA Quiet Aircraft Technology program, NASA and Pratt & Whitney (P&W) formed a collaborative partnership to develop an Ultra High Bypass engine demonstrator. The goal was to verify the potential advantages in reducing fuel burn, noise and emissions that could be achieved with an engine cycle having a fan to core flow bypass ratio of 13 and a fan pressure ratio of 1.3. P&W designed their engine, which they labelled the Geared Turbofan (GTF), with a geared Low-Pressure Core fan allowing the core and fan to operate at different speeds, thus optimizing the performance and reducing the complexity of the core.

NASA UHB Fan Noise Reduction Research

To help meet the aggressive N+1 noise reduction goal of 32 dB cumulative below the Stage 4 noise regulation, the SFW Project supported a high fidelity wind tunnel experiment of a scale model UHB turbofan-simulator to investigate the potential of two advanced noise reduction technologies, called Over-the-Rotor (OTR) metal foam acoustic treatment and Soft Vanes (SV) acoustically treated stator vanes, for the UHB engine cycle (Figure 4.181).The technologies were developed in a partnership between the NASA Glenn Research Centre and the NASA Langley Research Centre.The testing was conducted in the NASA Glenn 9'x15' LSWT using the Glenn UHB Drive Rig propulsion simulator at test section velocities simulating aircraft take off, approach and landing speeds.The goal of these two technologies was to reduce the noise generated by the fan rotor, and that generated by the interaction of the rotor wakes with the stator vanes with a minimum impact on the aerodynamic performance of the fan.

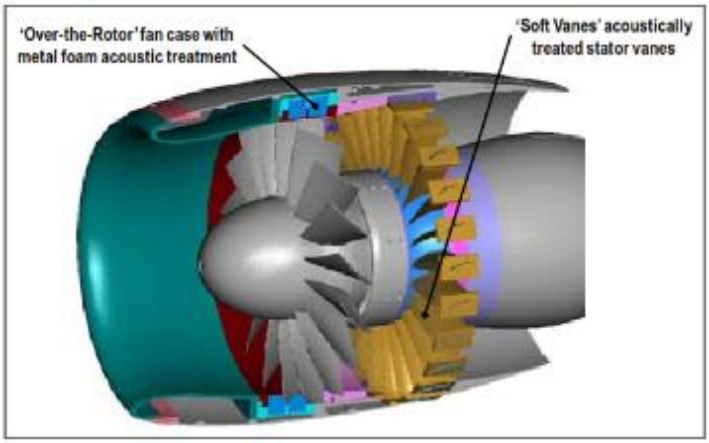


Figure 4.181: Illustration of the UHB Fan Model identifying the locations of two noise reduction technologies used during the NASA Ultra High Bypass Fan Noise Reduction Test, which were Over-the-Rotor acoustic treatment and Soft Stator Vanes.

The Over-the-Rotor acoustic treatment was designed to replace the traditional hard wall fan case and rub strip over the fan tip. The new design consisted of a 0.10" thick perforated hard plastic polymer flow surface with a 1.5" thick porous metal foam material behind it and contained within a steel shell which interfaced with the rest of the model hardware. The hard-plastic flow surface had 0.035" holes drilled into it resulting in a 20% open area and allowing the acoustic pressure disturbances to pass through into the metal foam liner behind it. The size and number of holes were designed to minimize the impact on the fan aerodynamic performance. The metal foam had a density of 6% to 8% (or 94% to 92% open area) with extremely small holes of approximately 100 pores per cubic inch of material. The metal foam presented a random and tortuous path to the incoming acoustic waves, forcing dissipation of the wave energy internally in the foam.

The design allows the local acoustic waves on the vane suction surface to penetrate into the vane's four internal chambers, where the acoustic energy would dissipate.

POSSIBLE OR PREDICTABLE BREAKTHROUGHS

Ultra-High Bypass Ratio engines (UHBR) are being studied, but with very hard integration issues, since the fan diameter is even greater than that presently used. With this option, noise reduction would basically entail pushing the same technologies further than those presented above. However, it must be kept in mind that new noise sources could emerge from these more "open" engines, especially if traditional ones, such as fan and jet, are lowered. In this case, core machinery noise, such as compressor noise, turbine noise or even combustion noise would need to be considered. Currently, there is reasonable confidence that Open Rotors will be able to meet the strictest regulation of ICAO Annex 16 Chapter 14 in a few years. From a programmatic standpoint, the main framework for such integrated research is the CleanSky research program, which will allow the engine manufacturer Snecma to produce a demonstrator by the end of the decade. Through this platform, new noise technologies, such as 3D-optimized blade design and pylon blowing in order to strongly reduce the interaction of the pylon wake with the blades, will be demonstrated. Current liner-based technologies will probably be used less since they are both inefficient and impossible to insert into open architectures.

It is also worth mentioning that the most recent trends tend to locate these forthcoming Open Rotors (Figure 4.182) rearward, near the empennage, between two vertical stabilizers, both to gain from the masking effect for community and to increase comfort and safety for passengers. Currently, aircraft manufacturers have not yet chosen between the two competitive technologies of UHBR and Open Rotors, but this critical choice is considered imminent and was likely to arise before 2015. Neither the first nor the second technological route will be sufficient to meet the stringent new objectives defined by ACARE for 2050 (Figure 4.183).



Figure 4.182: Open Rotor mounted on Hera vehicle (Snecma) and under test at the S1 Onera wind tunnel and the simulation of interactions between the two propellers (Onera)

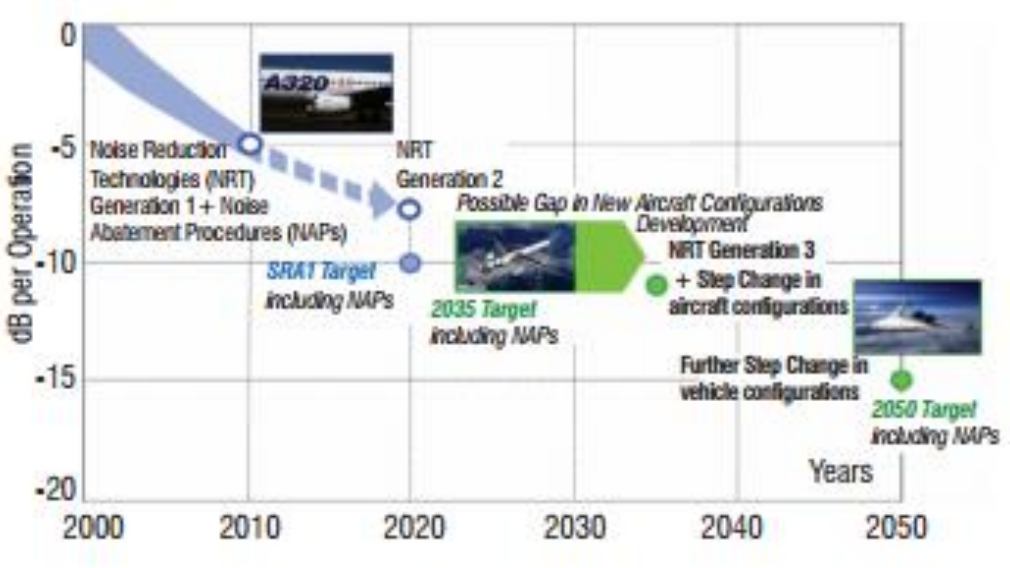


Figure 4.183: Further ACARE objectives for 2050

It is generally assumed that though 2020 objectives will be reached through enforcing new Noise Abatement Procedures (NAP) in addition to NRTs, 2050 objectives will require a breakthrough in aircraft architectures. Clearly, these most silent configurations would then involve integrating engines into the aircraft fuselage, or architectures where the engines would be completely shielded. Once again, these future configurations would strongly reduce both fuel consumption – through a dramatic reduction of the drag – and noise, with masking effects. Succeeding to build up such a configuration is a huge challenge since it would involve fully reinventing the entire aircraft with unexplored aerodynamic effects and brand-new propulsion systems. In particular, these engines would ingest air flows with intense distortion of the boundary layer, an unfamiliar configuration that remains to be addressed by research. However, the greatest challenge is probably not technical but commercial and psychological. Before engaging in such developments, manufacturers need to convince airliners of the expected benefits and the latter need to accustom their customers to the idea of embarking on such new aircraft. These challenges go far beyond technical issues.

Identification of Gaps

At this stage, it should also be pointed out that in aircraft noise reduction (Figures 4.50, 4.51) the main expectations are based on benefits associated with ducted turbofan engine concepts. Figures 4.50 and 4.51 show the US and EU "technology only" goals harmonized to TRL6 (reached till 2020) and a common metric. Their respective baselines and noise reduction target versus US and European research goals are also Table 4.15, where CAEP IEP2 Aircraft Noise Goals [ICAO, Doc 10127, 2019] for short-medium (2020) and medium (2030) term [Astley R. J., 2014] identified. The goals indicated in Table 4.15 for 2020 provide a reference for potential future developments, but confidence exist only for medium-term goals, which are combined with existing aircraft data for the same weight categories (Regional Jets RJ, Short/Medium Range two-engine aircraft SMR2, Long Range two-engine aircraft LR2 and Long Range four-engine aircraft LR4) over the period 1960 to 2015. Based on the findings (subchapters 4.1.1, 4.1.2 and 4.1.3), which asserted that technology and market performance of future notional Small Single Aisle and Large Single Aisle vehicle aircraft have the highest positive correlations with potential reductions in the contour area.

Currently, few things are known about the sources (Figures 4.54), but some preliminary work suggests that they could be more complex than expected. For instance, combustion noise is known to be divided into "direct noise" – i.e., sound directly stemming from the combustion process in the chamber – and "indirect noise", due to the conversion of vortices into sound waves through the turbine stages. "Direct noise" was thought to be more important than "indirect noise", however, a recent study tends to prove the contrary. Investigation work is still underway.

In addition to ultra-high bypass ratio (UHBR) engines, another strategy could also be to continue increasing BPR using Open Rotor architecture (Figures 4.55). Noise is then the most critical issue, along with safety: whereas single propellers radiate mostly tonal noise in the propeller plane, two counter-rotating rotors without nacelle radiate many tones over a wide frequency-range due to complex and intense noise interference mechanisms. Actually, the radiated frequencies combine all of the possible linear combinations between the two blade passing frequencies and this spectrum is propagated in all directions.

Ongoing research activities are facing this drawback and several tricks are being investigated to lower this excessive noise: tuning parameters, such as blades shape, blade length (especially differentiating the length between the first propeller and the second) and the gap between the two propellers, or even their respective rotating speeds or clocking, are among the various methods being experimented.

Looking on enormous progress reached in aircraft noise levels (Figure 4.25) and the noise footprint (aircraft produced today are 75% quieter than those of 50 years ago) reduction per aircraft movement, for example like only Rolls Royce (alone or with other engine manufacturers) has continued to improve aircraft engine design for fuel consumption, noise and engine emission in the last 15 years, as illustrated in Figure 4.26, and, of course, supporting new standard influence on aircraft noise exposure reduction around the airports, these new quiet aircraft typically output half the noise of the aircraft they are replacing, so air traffic movements can double without increasing the total noise output. In more detail, airport [Sustainable Aviation Noise Road-Map, 2018] predicts that as current aircraft are replaced by '*Imminent*' and '*Future*' aircraft, the noise exposure from EU aviation reduces by around 20% (Figure 4.27), which is close to EU forecasting (Figure 4.11). In 2014, ICAO adopted a standard Chapter 14 [ICAO Annex 16, 2019] that will result in a reduction of 7 EPNdB compared to the Chapter 4 Standard (Figure 4.26), so in-production aircraft are prohibited to be manufactured with noise higher than requirements. But introduction of new supersonic aircraft (SST 2.0) may disbalance reached progress for subconic aircraft transportation, if their requirements to noise will not be in accordance with Chapter 14 (as it is expected now – only Chapter 4 standard is looking achievable with existing technologies currently). So for particular airports in EU (around 10 in following decade), where the SST 2.0 will contribute to their noise exposure, and the expected overall aviation noise exposure reductions (by around 20% in Figure 4.27) will be much less. For community noise the SST 2.0 targets were considered as mid-term objectives for subsonic aircraft – *ICAO Chapter 4 - 10dB*. This new noise standard requirement is likely to apply to the future SST aircraft when operating in the subsonic speed regime to ensure some margin for operational flexibility and technological viability, this noise level of the SST will not be higher than current small business jets, as indicated in Figure 4.136.

In 2050, the effect of aviation on the atmosphere is fully understood, in that number by noise. A combination of measures, including technology development, operational procedures and land use planning inside the noise zones around the airports mean that aircraft noise impact has been mitigated at a rate outweighing the effects of increasing traffic levels. Of note is that under the advanced aircraft technology scenario (Scenario 4), from about 2030 onwards, the total yearly average DNL contour area and global population exposed to noise above 55 DNL may no longer increase with an increase in traffic. But Scenario 4 – the advanced aircraft technology and moderate operational improvement case – assumes a *0.3 EPNdB per annum for all aircraft entering the fleet from 2013 to 2050* [ICAO Environmental Report 2016]. Similar scenario for 47 airports within the EU have seen their L_{den} and L_{night} contours and the total population residing inside the L_{den} 55 dB and L_{night} 50 dB contours will also reduced even for scenario of Global Growth (mostly optimistic) (Figure 4.11, Table 4.2). This forecast assumes that there will be *no further airport expansion* and *no change in population* around these airports. The total noise energy in the EU28 and EFTA region follows flight counts closely (Figure 4.12) but was 5% lower in 2017 than in 2005, indicating that noise technology has managed to compensate for the increase in average aircraft size. The average noise energy per flight indeed went down by 14% over this period. Figure 4.12 presents the relative evolution of key air traffic and environmental indicators since 2005 and it shows an increase in economic and connectivity benefits from aviation (measured in passenger kilometres flown) with a lower rate of increase in environmental impacts.

Global impact of COVID-19 (Figure 4.18) on aviation, tourism, trade and economy is not included in consideration just now, because COVID pandemia is still continuing and its final results still not understandable for decision-makers. Never mind that first projections (Figures 4.18 and 4.19) are showing the similar effects in comparison with previous crises in aviation sector.

The introduction of an UHBR engine comes with the expectation of a significant noise reduction on the ground compared to an engine with lower bypass ratios, due to the reduced fan pressure ratio and jet exit velocity. A disadvantage of a UHBR in terms of noise is described in [Leylekian, L., Lebrun, M., Lempereur, P. 2014]. As the bypass ratio increases, an efficient nacelle has to be sized accordingly. A bigger nacelle results in additional and possible unacceptable weight and drag. Therefore, the nacelle of a UHBR has to be reduced in terms of length and volume in order to keep weight and drag acceptable. The reduced length, however, reduces the liner effectiveness, both at the front and back. Some technologies to overcome this disadvantage are described in [Leylekian, L., Lebrun, M., Lempereur, P. 2014]. Furthermore, the exhaust may interact more easily with the flow around the aircraft. These effects have to be considered when dealing with UHBR. For the initial noise assessment in this study no liners or additional interaction effects were considered.

As populations in megacities continue to grow, the increased urbanization and traffic situation is pushing ground transport systems to their limits. Bringing urban mobility to the third dimension offers the potential to create a faster, cleaner, safer, and *more integrated transportation system*. Urban Air Mobility (UAM) refers to a range of vehicle concepts and missions operating in a community, from small Unmanned Aerial Systems (sUAS) to vehicles large enough for several passengers. Setting up a suitable UAM infrastructure is a major challenge for any city. Airbus predicts that, by 2030, the UAM market will be worth an accumulated $50 billion, less than half of which will go to vehicle makers. Electric propulsion is seen as a key technology that could enable these kinds of systems, across the range of vehicle types and sizes. The embracement of mostly electric or hybrid UAM will contribute to low carbon and resilient cites, in line with EU policies, conducting in different tasks dedicated to energy and environmental impact. New aircraft technologies for increased mobility are likely to lead to new sources of community noise – *unfortunately even the latest version of [ACARE, 2016] is not looking on this subject at all*, though there are already over 200 sUAS concepts currently in development [https://evtol.news/directory/]. It is an evident gap in [ACARE, 2016] and not only concerning to noise reduction.

Many of these sUAS (Table 4.28, 4.29) are harnessing electrical power in a bid to be more environmentally and economically sustainable, with multiple electric vertical takeoff and landing (eVTOL) aircraft taking shape. The market of eVTOL concepts is broadly diversified, with a common set of technologies such as electric propulsion. Other programs are looking beyond electricity to alternative energy sources such as hydrogen fuel cells. Compared to a traditional single main rotor helicopter with combustion engine, an eVTOL should be significantly quieter, more reliable and safer and significantly less expensive. At flying altitude, noise from advanced eVTOLs will be barely audible. Even during take-off and landing, the noise will be comparable to existing background noise. Our preliminary first order noise analysis (Figure 4.156) showed that noise exposure is expected to be more severe near the take-off and landing areas. Noise level comparisons are shown for Robinson R22 and it's quieter versions in Figure 4.157. Size of noise contour (Figure 4.158) represents enclosed area exposed to noise levels of 65 dBA and above. It is observed that even in a scenario where the helicopter is 30 dBA quieter than original helicopter (i.e., R22-30), there is small area for arrival and larger area for departure mode around the heliport that experiences maximum noise level of 65 dBA or more`[Johnson W., Silva C., Solis E., 2018].

The vision for 2030+ is to demonstrate innovative and disruptive technologies, enabling new aircraft performance levels, and opening up new business models. By mid-2030, the mobility of people and goods is expected to undergo progressive changes, especially over distances of less than 500 km (inter-urban regional connections). Innovations and technologies related to propulsion, optimisation of different fuel types and airframe characteristics will reach higher levels of maturity, becoming available for regional air transport as well as other present and future air vehicles operating in that distance frame. Air vehicles operating in this range and operational environment (including regional aircraft with a capacity of up to 80 seats) are

considered the first application in the scheduled air transport system that will adopt hybrid-electric propulsion technologies for reducing the environmental footprint, toward climate-neutral aviation. Air vehicles operating at smaller distances or on thinner routes will also benefit from electric propulsion solutions tested on regional aircraft testbeds, by sharing the development of power modules and making use of different approaches to air vehicle integration.

An approach by consensus based on expert's judgement, assessment of the TRL situation and results from the technology evaluation exercises have then been used to perform the 2015 progress assessment, coming up with updated progress achievement figures and formulating associated recommendations for future research. Recommended Phased Approach to meet ACARE Noise Goal #1 includes analysis of expected advances on noise reduction with Noise Reduction Technology 1 (NRT1) and NRT2, as well as the Noise Abatement Procedure, (Figure 4.40, 4.70).

Aircraft noise was determined to be perhaps the most significant near-term constraint for On-Demand Mobility (ODM) Aviation operations. Noise emissions from aircraft and helicopters have historically been the most protested community impact of airports. Such public action has frequently placed pressure on regulatory authorities and government entities to limit or prohibit some aviation operations. As a result, aircraft noise from ODM aircraft was anticipated to indirectly influence the location and operation of Takeoff and Landing Areas, the type of aircraft that may be used, and the market demand for ODM Aviation services.

Noise from aircraft, and other transportation modes, is a complex topic spanning acoustics, the physiological way humans experience noise, and the psychological perceptions listeners have of the source of the noise and what it represents to them. A large body of research spanning this area has been conducted over the last century, with learning outcomes relevant to modern aviation [M. Basner, et al., 2017; National Research Council, 2002]. EU project ANIMA [Dimitriu D., Heyes G., Hooper P., 2018] stands for "Aviation Noise Impact Management through Novel Approaches" is a people-oriented research with aims at identifying and diffusing best practices to lower the noise annoyance endured by communities around airports. The ACARE SRIA should confirmed the importance of addressing the impacts aspects as part of a coordinated research strategy, stating that the targeted 65% noise reduction relative to the 2000 baseline "should be achieved through a significant and balanced research programme aimed at developing novel technologies and enhanced low noise operational procedures, complemented by a coordinated effort providing industry, airports and authorities *with better knowledge and impact assessment tools to ensure that the benefits are effectively perceived by the communities exposed to noise from air transport activities*".

For long-tern goal (2050), defined by [ACARE, 2016], the gap between the goal – "*the perceived noise emission of flying aircraft is reduced by 65%*" – and expected aircraft noise for RJ, MR, LR types in 2030 is still a subject for research and innovations. The goal for aircraft noise in [ACARE, 2016] is formulated as completely technology goal, in contrast with ICAO Policy goal "*Limit or reduce the number of people affected by significant aircraft noise*" [ICAO Resolution A40-17, 2019], which is defining the impact value by noise – really the final goal in environment protection from noise.

It is clear that between alternative transport modes aviation's impact on climate change deserves special attention. Due to typical flight altitudes in the upper troposphere and above, the effect of aircraft engine emissions like e.g. water vapour, nitrogen oxides and aerosols on radiative forcing agents is substantial (Figure 4.91). It is thought that doubling of aircraft movements in the next 30 years will increase the impact of aviation on global climate (Figure 4.2) and the emissions could unlikely to be stabilized at levels consistent with risk-averse climate targets without restricting demand (Figure 4.4).

According to Schilling 2016's report [Schilling T., Rötger., T, Wicke, K. 2016], the objectives set by the aviation industry in 2009 cannot be met especially the long-term reduction goal of CO_2 emissions by 2050. AIRCAT project is a collaborative work of IATA and DLR to identify possible challenges, obstacles and roadblocks to the deployment of new technologies. They selected three aircraft designs of low-emissions concepts as battery-driven, hybrid wing body and strut-braced wing with open rotor design. In addition, analyse two

types of low-carbon alternative fuels as drop-in solar jet fuel and natural liquid gas. Consequently, they assessed that the majority of emissions reductions necessary to meet the 2050 goal would have to come from low-carbon fuels and radically new fuels. Another study is coming with Hassan et al. (2017, 2018)'s criticism regarding the challenges. The paper [Hassan M., Pfaender H., Mavris D.N., 2018] investigates the achievability of IATA/ICAO targets in the USA using a top-down partial equilibrium model of the aviation system complemented with a previously developed fleet turnover procedure. Results show that biofuels have the most impact on system CO_2 emissions, responsible for an average 64% of the total savings by 2050 (with aircraft technologies and operational improvements responsible for 31% and 5%, respectively). However, this impact is associated with high uncertainty and very dependent on both biofuel type and availability. Hassan et al. [Hassan M., Pfaender H., Mavris D.N., 2017] studied the feasibility of the aviation goals on CO_2 emission reductions designated for 2050 and by considering 40 different scenarios they found that these goals *are not feasible* because of the high demand growth. Moreover, with medium or low demand growth coupled with high technology introduction rates and faster retirement of old aircraft they found that the goals are feasible. To achieve the 2050 goals, step changes in aircraft configuration and operation (including alternative energy sources) will be required (Figure 4.20) – currently envisaged evolutions will not be sufficient [Strategic Research and Innovation Agenda, 2017], there is a need a real basket of measures! – Figure 4.20.

Beyond travel demand, [Heinemann P, et al, 2017] analysed tube and wing configurations in terms of reaching the Flightpath 2050 goals. They used simplified methods to model the technologies and produce statements on how fuel burn was changed on the overall aircraft level. Finally, they found that with selected technologies in the study it was not likely to reach any of the goals. They proposed that for reaching the aforementioned goals of EU considering noise and NO_x goals radical approaches would be necessary for the airframe and the propulsion system. It was asserted that NO_x is playing the most important role in the promotion of CO_2 assimilation and nutrient N and P in drainage should be used for fixing CO_2 and protecting global warming.

The rate of NO_x formation grows with the temperature rise in the combustion area reaching the maximum values at ratio air-fuel close to stoichiometric one. Consequently, to provide a low level of NO_x emissions the time spent for mixture combustion at high temperatures shall be minimized. The example of implementation of such approach providing the margin as for harmful substance emissions relativeto the ICAO regulatory requirements serves the combined technology Rolls-Royce "Phase 5" employed in Trent engine series [Parker R., Lathoud M., 2010].

During the combustion of hydrocarbon-based fuels, aircraft engines generate gaseous and particulate matter (PM) emissions. At the engine exhaust, particulate emissions consist mainly of ultrafine soot or black carbon emissions. These particles, referred to as "non-volatile" PM (nvPM), are present at high temperatures, in the engine exhaust. ICAO/CAEP agreed on an end date for the Smoke Number Standard, of 1 January 2023, as the new nvPM emissions Standards preserve ICAO smoke visibility limit [ICAO Annex 16, 2019]. With this new Standard, ICAO will have completed the main environmental Standards for the certification of aircraft and engines, namely for noise, local air quality (NOx, HC, CO, nvPM) and climate change (CO_2), making the aviation industry the only sector with mandatory environmental certification requirements at the global level for the operation of its equipment. Once applicable, all new aircraft will need to be certified to these ICAO Standards before operating. *Among the Challenge 3 goals from ACARE any targets for nvPM emission reduction is absent.*

Alternative fuel usage is another option among researchers. However, according to [Noh et al., 2016] using alternative energy fuels has other research issues that should be met in future. There was examined alternative energy bio-jet fuel with maintenance perspective and based on their evaluations they asserted that the use of biofuel would offer the benefit to aircraft maintenance. In addition, they argued that global aviation world needs to be underpinned by the awareness of the good effect of the usage of biofuel on engine process and procedure.

It is clear that dealing with global warming and climate change issue is holistic and should be analysed with a systemic perspective. Lue at al. [Luè A., et al., 2016] presented the main results of 'REACT: A European Strategic Research Agenda for climate-friendly transport' project, which was co-financed by the European Commission, in their study. Based on their findings, technology alone would not be sufficient to achieve the necessary reductions in carbon emissions and they proposed that integrated solutions should be necessary. For instance, technological improvements might offer significant GHG reduction potential, but strong interventions in policy schemes would be needed. In addition, they asserted that long-term technological solutions could not be treated independently from the short-term behavioural change and behavioural and social changes should be recognized as paramount. Therefore, they concluded that there was a number of vital reasons why significant climate policy for the transport sector was not being effectively developed at the EU supranational level and implemented in member states.

The typical time between aircraft generations replacing each other is in the order of 20 years, sometimes longer. With new aircraft models currently being introduced in almost all seat categories, it is uncertain if the next generation of aircraft will arrive before the 2030s except in the 211 – 300 seat category, as seen in Figure 4.184.

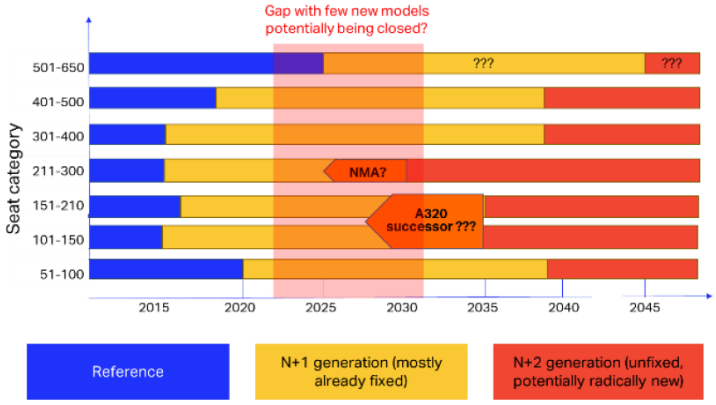
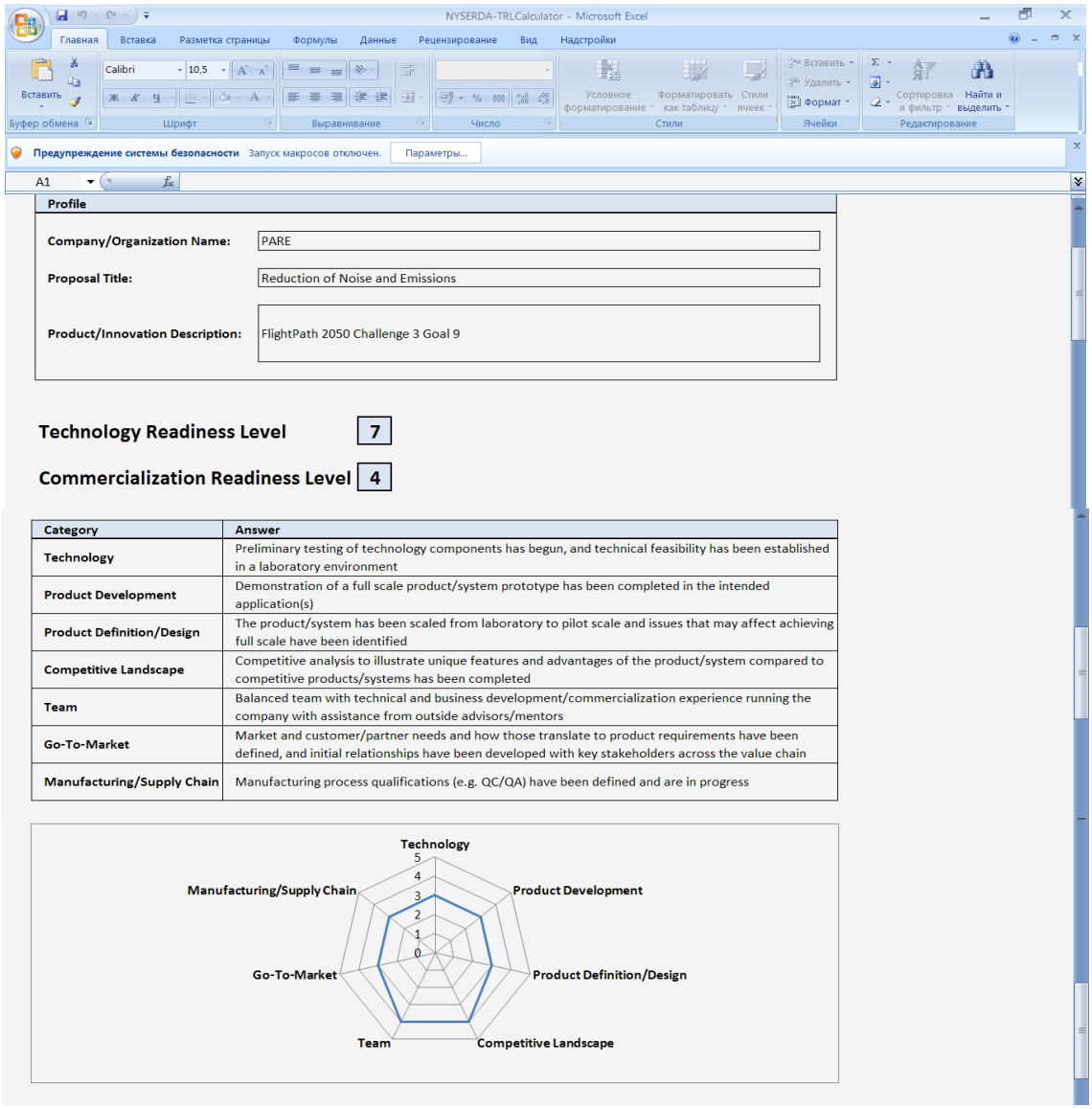


Figure 4.184: Expected sequence of future aircraft generations in different seat categories, including recent indications on new developments

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 9**"Reduction of Noise and Emissions" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.185 grounding on the results of the 1st year PARE report (PARE D1.1, 2018).



Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Demonstration of a full scale product/system prototype has been completed in the intended application(s)
Product Definition/Design	The product/system has been scaled from laboratory to pilot scale and issues that may affect achieving full scale have been identified
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Market and customer/partner needs and how those translate to product requirements have been defined, and initial relationships have been developed with key stakeholders across the value chain
Manufacturing/Supply Chain	Manufacturing process qualifications (e.g. QC/QA) have been defined and are in progress

Figure 4.185: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 9** "Reduction of Noise and Emissions"

4.2 Emissions Free Taxying at Airports

**Flightpath 2050 goal 10: "Aircraft movements are emissions free when taxing".*

Historically, any effort related to efficiency improvement has mainly focused on the airborne phase, but due to the increasing restrictions, nowadays the ground phase of the flight mission (i.e. taxiing) is also being addressed. Taxiing can be divided into taxi-out and taxi-in. Taxi-out is part of the taxiing from the parking position until the moment of take-off. Taxi-out phase is preceded by the aircraft push-back. Since main jet engines cannot provide reverse thrust, additional tractors and tugs are required to move the aircraft backwards. When aircraft reaches the border to the manoeuvring it is handed to the ground controller which guides it to its assigned runway. Since engines are optimised for cruising speed, they are highly inefficient when used in idle mode and therefore taxiing is addressed as one of the biggest contributors to the pollution and noise at the airports.

During taxiing, the aircraft engines are set to idle mode. The taxiing of aircraft on engine power and the use of auxiliary power units (APU) on the ground can be significant contributors to emissions at airports and also generate noise. This means that the engines are operating in a non-optimum thrust range because they are designed to be fuel-efficient at the airborne phase of the flight only. Furthermore, at highly congested airports, the taxiing-out time can exceed ~30 minutes, leading to considerable fuel burn and high emission rates. In fact, more than 56% of the total NOx generation in 2002 at Heathrow airport was due to taxiing [Dzikus N., Fuchte J., Lau A., Gollnick V., 2011], whereas this value is estimated around 2% at Zurich airport [Fleuti E., Maraini S., 2017]. The cost of fuel used for taxiing is expected to reach over $7 billion by 2020, emitting over 23 million t of CO_2 and amounting to over $440 million in CO_2 tax emissions penalties [Vaishnav P., 2014]. In addition to the already mentioned 2050 requirements, also all taxiing procedures are required to be carbon neutral by 2050. The most obvious way to achieve goal 10 is to use electric towing vehicles. For on-ground activities, the electric taxiing (ET) methodology is one of the suggested solutions for reducing the emissions and the acoustic noise in the airport, and for lowering the fuel consumption and operating costs. There are technical aspects like ensuring compatibility of towing brackets and sufficient traction power. Also infrastructure aspects with recharging facilities for a fleet of electric towing vehicles. At last, but not least, the coverage of the initial investment and operating cost. These must be seen in the context of lower environmental impact.

- Input:

- fuel spent and emissions associated with taxiing at airports: worldwide and at specific airports
- availability of vehicles, infrastructure and other costs

Several solutions have been proposed as an alternative to the conventional taxiing and, in a broad sense, they can be categorized into operational and technological methods [Khammash L., Mantecchini L. Reis V., 2017], as illustrated in Fig. Figure 4.186. The currently preferred battery technology for ground movements at the airport or on the airfield and in the aircraft itself is the lead-acid and the nickel-cadmium battery.

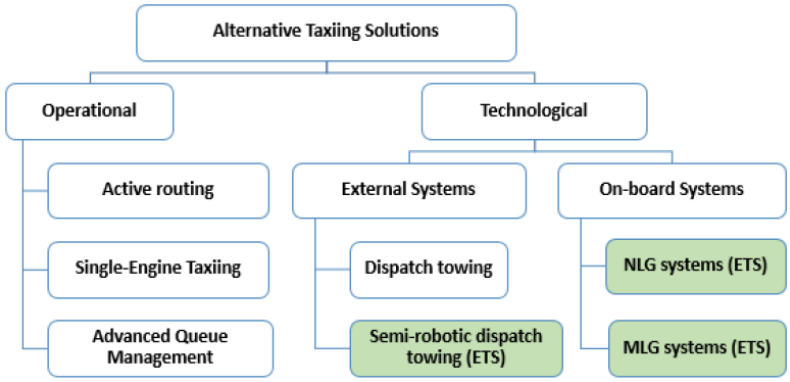
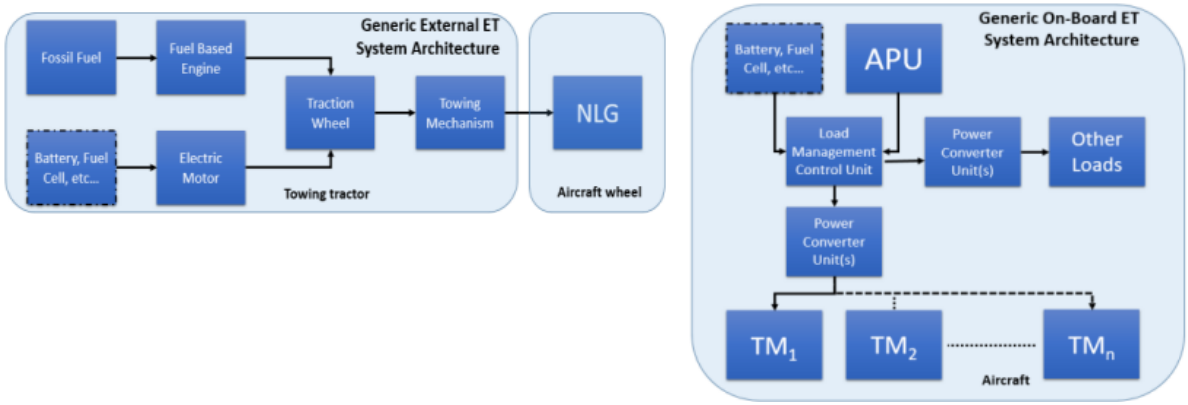


Figure 4.186: The proposed categorisation of alternative taxiing solutions

The operational measures involve the improvement of operations at the airport level and they have already been relatively successful due to the ease of their implementation. The most prevalent method is the single-engine taxiing, in which only one engine is used for aircraft movement. Other techniques, such as active routing and advanced queue management, are based on the ground traffic optimisation to reduce taxiing times. On the other hand, technological solutions are based on the employment of a particular technology that allows for smarter and greener taxiing. The main difference between these two options is that operational solutions still require the use of engines for the ground movement, while the technological ones are engineless-based approaches. The latter, in turn, can be grouped into 1) on-board and 2) external systems.

Application of external systems relies on a car-like vehicle to perform towing of the aircraft. The so-called dispatch towing method employs the standard towing tractors already used for pushback, which burn diesel, gasoline or natural gas that are all cheaper than aviation fuel. Even though emissions from the on-ground vehicles are increased in total, this method shows fewer emissions on average compared to conventional aircraft engine-based taxiing. The semi-robotic dispatched towing employs more efficient and environmentally friendly electric (fully or hybrid) trucks for towing purpose. Instead, on-board systems are entirely located in the aircraft and they rely on the concept of an electrical drive system (EDS), which typically consists of an electrical motor, a power converter, a control system, and an electric energy source. An advantage of on-board systems is the improved aircraft's autonomy, as it does not depend on ground crew or equipment, as well as the capability of implementing regenerative braking. An electric traction motor (TM) is installed in the wheel of either the nose landing gear (NLG) or the main landing gear (MLG).

All on-board and external semi-robotic towing solutions embrace the MEA initiative, as they use electric energy at one point of the energy conversion stage. Therefore, these engineless options can be named as electric taxiing systems (ETSs). A generic system architecture for both on-board and external systems is shown in Fig. 4.187, where APU stands for the auxiliary power unit. In addition, all of the described ETSs have demonstrated technological readiness level TRL 5 or higher.



a) b)

Figure 4.187: A generic system architecture for both (a) external and (b) onboard ETSs

The primary advantage of using external ETSs, compared to other alternative solutions, is that these are non-invasive to the aircraft design. This feature facilitates the certification process and consequently encourages the approval and adoption by airline operators. It also means that no extra weight is added onboard the aircraft. Modifications to the airport infrastructure ought to be made, such as new roads for tractor movement after the aircraft's take-off. Also, using external ETSs during taxi-in faces logistic efforts associated with connecting the tractor to the arriving aeroplane; thus, potentially lengthening the taxiing-in time. Despite the drawbacks, these systems proved to be popular among airlines with some of them currently being operational worldwide, as detailed in the upcoming subsections.

Both the NLG and MLG configurations have advantages and drawbacks. Hence, the selection between them is a trade-off study among many aspects. First of all, the NLG layout benefits from the larger available space, which is not the case of MLG due to the presence of the braking system. Despite the confined available space, the MLG carries around 90% of the aircraft weight, making it particularly appealing for the motor installation due to the higher available traction forces. Thus, at severe weather conditions such as snow, ice, and rain, when the tyre-road adherence is weakened, the performance of the ETS installed inside the NLG would be problematic. In narrow-body aircraft, the MLG is equipped with four wheels, and theoretically, four electric motors could be mounted within the gears. For on-board ETSs, electrical energy can be provided by sources already available on the aircraft, such as the APU starter/generator (S/G) and the integrated drive generator (IDG) driven by the main engine. Therefore, alternatively, energy can be supplied 'more electrically' and 'greener' through 'localised' batteries and fuel cells (water as only waste) or a combination of all of them. The feasibility and economic of emissions – free-taxiing thus critically depends on the available battery technology (Key Topic T4.2).

KEY TOPIC T4.2 – AIRCRAFT MOVEMENTS ARE EMISSIONS FREE WHEN TAXING

Benchmark / State of the Art - Battery

Aircraft:

a. Internal engine starter generator (ESG) set
b. The auxiliary power unit (APU) which includes battery and super/ultra-capacitor
c. Flight control actuation, and a fault-tolerant Power Management and Distribution (PMAD)
d. Motor drive system

Other motorized movements at the airport:

a. Moving the aircraft from the gate to the starting position
b. Other motorized movements at the airport

Both technologies are long in the field and therefore technically very mature but suffer from insufficient energy density and cycle life. In order to meet the future requirements, substantial improvements in energy density, lifetime, cost and charging infrastructure are needed. The following Tables 4.35 – 4.38 give an overview of the most important key figures of common battery systems.

	Characteristics	Ni-Cd	Ni-MH	Lead Acid	Li-Ion
1	Cell voltage / V	1.25	1.25	2	3.7
2	Spec. energy density / Wh kg^{-1}	40-60	60-90	30-50	50-250
3	Energy density / Wh dm^{-3}	150-190	300-340	80-90	100-700
6	Cycle life	1000-1500	500-1000	200-300	300-10000
7	Operating Temperature / °C	-40 to 60	-20 to 60	-20 to 60	-20 to 60
8	Self-discharge / month	20 %	up to 30 %	5 %	<5 %
9	Overcharge tolerance	Moderate	low	high	Very low
10	Maintenance	1-2 month	?	3-6 month	Not required

Table 4.35: Comparison of different types of battery chemistries [adapted from Gianfranco Pistoia, "Batteries for Portable Devices", Elsevier 2005]

	Battery manufacturer / *model nr.*	Chemistry	Aircraft	System Voltage / V	Capacity / Ah
1	Saft-*2758*	Ni-Cd	A320	24	23
2	Saft- *4059*	Ni-Cd	A340	24	40
3	Saft-*405 CH*	Ni-Cd	A330	24	40
4	Acme Aerospace Inc-263BA101-*2*	Fibre Ni-Cd (FNC)	B-777	24	47
5	Saft-*539 CH1*	Ni-Cd	B-737NG	24	53
6	Saft-*539 CH1*	Ni-Cd	B-767-400	24	53
7	Saft-*539 CH2*	Ni-Cd	A380	24	50
8	GS Yuasa *LVP-40-8-65*	Li-Ion	B-787	28.8	75
9	Saft-*40176-7*	Ni-Cd	B_747 x	24	40
10	Concorde *RG150-1*	VRLA	B-717	24	3.5
11	Marathon *Nacro 7-75M3-120*	Ni-Cd		8.4	75

12	Concorde *D8565/5-1*	SLA, lead acid	C-130	24	30
13	Concorde *D8565/11-1*	SLA, lead acid	C-141, F4	24	10

Table 4.36: Details of batteries used in different aircraft [Adapted from a. Aircraft batteries - current trend towards more electric aircraft IET Electr. Syst. Transp., 2017, 7, 2, 93-103]

	Li-ion*	Ni-Cd**
Nominal cell voltage / V	3.20	1.20
Battery voltage / V	25.6	24.0
Capacity / Ah	45-55	23
Energy / Wh	1280	552
Typical battery cost / US $	~21.000	~6.500
Battery Costper Wh / US $	16.4	11.1
Spec. Energy density, Wh/kg	110.0	21.65
Weight / kg	22-25	26

**EagerPicher Technologies, LLC MAR-9526 (LFP), ** SAFT* 410946 Mod. 2758

Table 4.37: Comparison of Li-ion and Ni-Cd aircraft grade batteries [Adapted from a. Aircraft batteries - current trend towards more electric aircraft IET Electr. Syst. Transp., 2017, 7, 2, 93-103]

	Cell level energy density Wh/kg	Cell level energy density Wh/L	Durability cycle life 100% DoD	Price estimate US$/ Wh	Power C-rate	Safety thermal runaway onset, °C	Voltage / V	Temperature range in ambient conditions °C
$LiCoO_2$	170-185	450-490	>500	0.31-0.46	1 C	170	3.6	-20 to 60
$LiFePO_4$ (EV/PHEV	90-125	130-300	>2.000	0.3-0.6	5 C cont. 10 C pulse	270	3.2	-20 to 60
$LiFePO_4$ (HEV)	80-108	200-240	>2.000	0.4-1.0	30 C cont. 50 C pulse	270	3.2	-20 to 60
NCM (HEV)	150	270-290	>1.500	0.5-0.9	20 C cont.	215	3.7	-20 to 60

					40 C pulse			
NCM (EV/PHEV)	155-190	330-365	>1.500	0.5-0.9	1 C cont. 5 C pulse	215	3.7	-20 to 60
Titanate vs. NCM/LMO	65-100	118-200	>12.000	1-1.7	5 C cont. 10 C pulse	Not susceptible	2.5	-50 to 75
Manganese spinel (EV/PHEV)	90-100	280	>1000	0.45-0.55	3-5 C cont.	255	3.8	-20 to 50

Table 4.38: Summary of the main (Automotive) Lithium-ion types / State of the art [Adapted from Johnson Metthey Technol. Rev., 2015, 59, (1), 4-13

TAXIING CONCEPTS

- Off-Board Systems
  - **Hybrid-Electric Tractor for Taxiing "TaxiBot"** [TaxiBot, "TaxiBot Product Homepage," Available: http://www.taxibot-international.com/ ,[Accessed 11 2017]
  - **Electric Schlepper "eSchlepper"** [E-PORT AN, „Homepage",Available http://www.e-port-an.de/projekt/die-neuen-e-fahrzeuge/eschlepper.html], [Accessed 11 2017]
  - **Taxiing Vehicle by Airbus,** [Airbus, http://www.aircraft.airbus.com/innovation/future-by-airbus/smarter-skies/low-emission-ground-operations/, [Accessed 11 2017]
  - **Trace Towbot,** [http://towbots.us/,[Accessed 11 2017]

- On-Board Systems
  - **Electric Taxiing Systems (ETS)/ Green Taxi Systems (On-Board)**
  - **Battery/fuel cell-based Electrical Energy Storage Systems (ESS),** [http://www.wheeltug.gi/, [Accessed 11 2017]; http://www.env-isa.com/en/expertise/egts-electric-green-taxiing-system-safran/, [Accessed 11 2017]

In 2005, the first proof of an ET concept was positively demonstrated by the company WheelTug. It was an on-board system installed at the NLG of a Boeing 767 loaded with 94% of its maximum take-off weight (MTOW). Since then, numerous studies have been conducted highlighting both economic and environmental benefits related to the ETSs utilization.

An example of external ground propulsion system is TaxiBot, a system developed by Israeli Aerospace Industries. TaxiBot is a semi-autonomous hybrid electric tractor, shown in Figure 4.188b, designed to tow the aircraft during all taxiing procedure (push-back, taxi-out and taxi-in). The powertrain of this tractor consists of two diesel engines each driving a separate electric generator which supplies 8 electric motors installed in 4 wheels. Maximum power to the road is 500 kW with maximum achievable torque of 45 kNm [TaxiBot-International, 2018]. With these numbers, the tractor can reach a speed of 23 knots towing a full Boeing 737. In May 2017, TaxiBot was certified by EASA for the A320 family (both ceo and neo), followed by the Federal Aviation Administration (FAA) certification for Boeing 737 family in October 2017. EASA's

certification is also valid for the FAA. Thus, TaxiBot is the only certified and commercially-operational alternative taxing solution up to date (in 2018).



a)



b)

Figure 4.188: Examples of external electric taxiing systems: (a) Tesla-X towing the empty Boeing 787-9 with a mass of 130,000 kg; (b) TaxiBot at Frankfurt airport

Electric landing gear drive equipped with traction motors can provide taxi capability without the use of main engines or tractor. WheelTug was the first company to demonstrate the operation of an on-board electric taxiing system, as shown in Figure 4.189, back in 2005. The system depends on two induction machines from Chorus Motors, located at the NLG. The APU powers the motors during the taxiing. This solution still uses fossil fuel product and hence it is not completely emission and noise free, although levels are much lower than during normal taxiing operation. Designers of this system highlight several benefits of using WheelTug in addition to the general benefits of electric taxiing that have already been mentioned. Firstly, this system has the advantage of reducing the push back time to 8 minutes per flight, which is a significant time reduction especially for short and medium haul flights. Also, WheelTug emphasizes the possibility of parking parallel to the terminal building, since jet engines are turned off. Consequently, two airport bridges can be used for boarding increasing the passenger comfort and more importantly it would reduce the turnaround time (TAT) and consequently the cost of the flight. Following the successful demonstration activities of WheelTug, developments of electric taxiing continued with other companies. Collaborations between the German Aerospace Centre (DLR) and Lufthansa Technik is one of them. The DLR motor is located also at the nose landing gear (NLG) and consists of a permanent magnet synchronous motor (PMSM). The two motors and gears installed in the wheel rim are shown in Figure 4.190.



Figure 4.189: WheelTug system implemented in NG



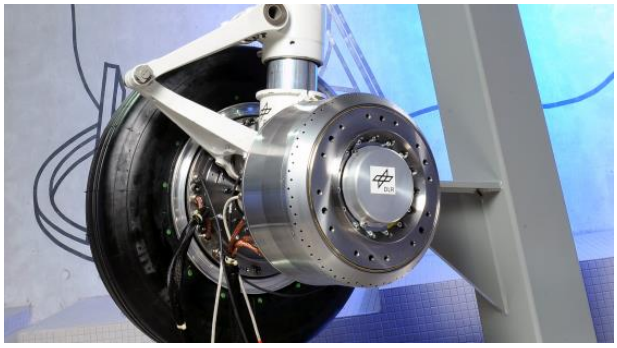


Figure 4.190: Motor Developed by DLR

All the systems discussed above are installed at the NLG. Regarding the MLG configuration, Safran has advanced the furthest in collaboration with other companies and universities. Safran and Honeywell Aerospace created a joint venture in 2011 called the Electric Green Taxiing System (EGTS). The system was designed in accordance to the EGTS requirements, namely 1) 20 knots speed in 90 sec, 2) 10 knots speed in 20 sec for active runway crossing and 3) breakaway torque at 1.5% slope at maximum take-off weight (MTOW). The system was successfully tested at the Paris International Air Show (PAS) in 2013 using an A320, as shown in Figure 4.191.

All presented systems assume engineless operation, i.e. jet engines are turned-off during taxiing. However, none of them is fully electric and zero carbon, besides DLR which uses fuel cell with water as waste. Feasibility studies regarding economy and operations that have been presented showed that implementation of existing ET systems can potentially reduce CO_2, NOx and noise. However, Safran decided to stay devoted to the electric taxiing idea, through its involvement in the Clean Sky 2 framework. An important project in this framework, led by Safran Landing Systems, is known as "high energy storage module for an electric taxi" through which optimum energy storage system should be designed up to TRL6.

Safran has generated real industry buzz by offering the first electric taxiing solution, with an electric motor in the landing gear, powered by the APU, so that pilots no longer have to use their jet engines for taxiing (Figure 4.191). This innovative solution is now being developed with Airbus for the A320neo/ceo. The target date for entry into service is 2022. According to a study carried out with airlines, this system makes a lot of sense at busy airports with long taxiing times, as well as for carriers that operate a number of daily shuttle flights. With this new technology, they can reduce not only their operating costs, but also their environmental footprint.



Figure 4.191: Demonstration of EGTS from Safran: a) first electric taxiing solution; b) demonstartion on A-320

The use of superconducting motors should be considered as an alternative for the ET motors because they have a relatively high torque density. Authors in [43], [44] present a study of using it for propulsion application. Because of the confined space and the need for simplicity, it is more convenient to use active air cooling rather than liquid cooling. Furthermore, novel machine types can be further investigated for this application, such as IM with conical rotor.

On-board solutions are the most suitable for narrow-body aircraft, which have many flight cycles during the day with high taxiing time. For wide-body aircraft, the fuel savings during taxiing would be cancelled during the flight phase due to having extra on-board weight. Therefore, one possible scenario to be foreseen is a mixture of the two types: on-board for narrow-bodies and external systems for wide-bodies aircraft. However, the final decision will have to be made by the airline companies in accordance to their network and aircraft utilization. For instance, KLM's B737 which flies LHR-SCHroutemightseethebenefitsofon-boardsystem implementation, while no benefit would be seen for the same aircraft type flying between airports with small taxiing times.

In case of using on-board systems, installation of the ET at the main lading gears seems to be the more reasonable solution, as this is s responsible for carrying the majority of the aircraft weight. The motor configuration is challenging, as each configuration possesses several advantages and disadvantages. PMSMs are usually the first choice for ET traction motor, because of their high torque density and efficiency.

In summary, the choice of ETS is a trade-off, which depends upon cost, ease of implementation, kinematic performance, and both fuel and time savings. However, it can be concluded that at the moment, none of the presented systems has achieved any significant performance gap compared to other competitors. Even though the three most prominent systems (i.e., TaxiBot, WheelTug, and Safran ETSs) have different concepts, all of them claim similar environmental and economic benefits. A clear view of which ETS is optimal for a particular situation/scenario will be achieved only when these systems massively enter the market and when further airline demands drive the technology innovations.

However, it is also equally true that until AEA ultimately drive conventional and MEA out of market, something which is still way too far in the future, then the implementation of ETSs is a necessity for future aircraft to meet the 2050 targets, in terms of optimisation of travel and to be compliant with emissions policies. Nevertheless, a realistic prediction based on the most promising ETSs available today would foresee the following scenarios [**GiangrandeP., et al., 2019**]:

1) No major savings in terms of total taxiing time.
2) A potential reduction of block-fuel burns in the range of 1-4%, depending on the flight distance and the weight of onboard ETS.
3) There could be savings from as low as $50k up to $500k per year per aircraft.
4) The maximization of the advantages arising from the adoption of ETSs can be accomplished by alternating the employment of external and on-board ETSs, based on the airline fleet capability and the airports' characteristics.

Reference State in 2010 - Battery

Since the lead-acid batteries and the nickel-cadmium batteries are technically exhausted (Table 4.39), no significant improvement in the energy and power density is expected.Therefore, a reference value for 2010 is difficult to set for lead-acid and the nickel-cadmium battery. Rather, there is a shift to lithium-ion technology in the aviation industry.Lithium-ion chemistry offers a large variety of materials and cell architectures, which enables the possibility to design high-power as well as high energy systems. In this respect, it has to be noted again that choice of active material, which is able to reversibly insert and extract lithium-ions within vacancies in their crystal structure, decisively influences the amount of energy that can

be stored in LIBs. The commercial breakthrough of lithium-ion batteries did not happen until the discovery of these insertion compounds, also known as host matrices.

	Characteristics	Ni-Cd	Ni-MH	Lead Acid	Li-Ion
1	Cell voltage / V	1.25	1.25	2	3.7
2	Spec. energy density / Wh kg^{-1}	40-60	60-90	30-50	50-250
3	Energy density / Wh dm^{-3}	150-190	300-340	80-90	100-700
6	Cycle life	1000-1500	500-1000	200-300	300-10000
7	Operating Temperature / °C	-40 to 60	-20 to 60	-20 to 60	-20 to 60
8	Self-discharge / month	20 %	up to 30 %	5 %	<5 %
9	Overcharge tolerance	Moderate	low	high	Very low
10	Maintenance	1-2 month	?	3-6 month	Not required

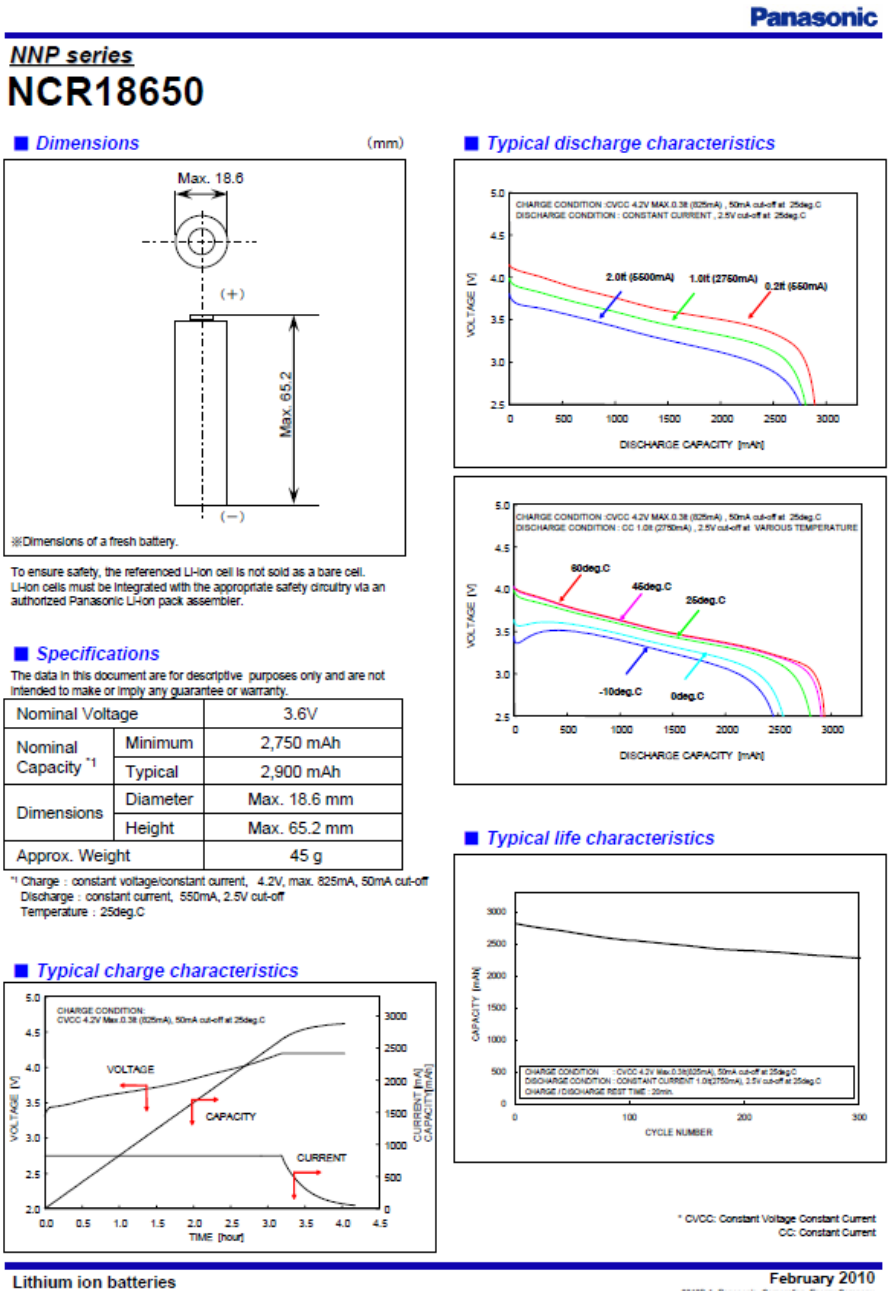
Table 4.39: Comparison of different types of battery chemistries [adapted from Gianfranco Pistoia, "Batteries for Portable Devices", Elsevier 2005]

For the lithium-ion technology, it can be stated that these are mainly based on carbon as the anode and transition metal oxides, as well as phosphate as the cathode material. This combination and its variation have been the state of the art for years. Increase in the energy density could be mainly achieved by optimizing the cell production process.As an example of the state of the art from 2010 for an energy cell (Figure 4.192), the Panasonic NRC18650 should serve with an energy density of about 230 Wh/kg.

Progress up-to-now - Battery

Since the lead-acid batteries and the nickel-cadmium batteries are technically exhausted, no significant improvement in terms of energy density, cycle life, calendar life etc. is expected.In the fields of lithium-ion batteries, the situation looks a bit more optimistic. In general, an increase in the energy density, with state-of-the-art chemistry, could be mainly achieved by optimizing the form factor and the cell production process. As an example, a Panasonic NRC1865 cell should be mentioned (Figure 4.193, 4.194) in which the energy density could be increased from 230 Wh/kg in ~2010 to 243 Wh/kg within the last years.

Nevertheless, even if the current (Li-Ion)- battery chemistry has proven itself, efforts are still to be made to increase the energy density as well as other key performance parameters to meet future requirements. In R&D advanced and post-lithium concepts are also considered, which are still far away from being commercialized.



Panasonic

NNP series

NCR18650

■ Dimensions (mm)

Max. 18.6

(+)

Max. 65.2

(−)

※Dimensions of a fresh battery.

To ensure safety, the referenced Li-ion cell is not sold as a bare cell. Li-ion cells must be integrated with the appropriate safety circuitry via an authorized Panasonic Li-ion pack assembler.

■ Specifications

The data in this document are for descriptive purposes only and are not intended to make or imply any guarantee or warranty.

Nominal Voltage		3.6V
Nominal Capacity *1	Minimum	2,750 mAh
	Typical	2,900 mAh
Dimensions	Diameter	Max. 18.6 mm
	Height	Max. 65.2 mm
Approx. Weight		45 g

*1 Charge : constant voltage/constant current, 4.2V, max. 825mA, 50mA cut-off
Discharge : constant current, 550mA, 2.5V cut-off
Temperature : 25deg.C

■ Typical charge characteristics

■ Typical discharge characteristics

■ Typical life characteristics

* CVCC: Constant Voltage Constant Current
CC: Constant Current

Lithium ion batteries February 2010

Figure 4.192: Specification sheet for the Panasonic NRC 18650

Predictions up-to-2025 - Battery

In our opinion, especially the development of batteries for ground-operation-vehicles (e.g. towing tractors) is closely linked to the development of batteries for automotive electromobility. Of course, there are some differences in the technical requirements. For example, a long driving range is for an airport vehicle less important than high power (e.g. towing tractor). On the other side for a small unmanned aerial vehicle (UAV) a high energy density of the battery is very important for travelling long distances.Therefore, one can´t give a solution that meets all requirements.Rather, it requires a tailor-made solution for different purposes. However, in the following some information on the necessary developments regarding (state of the art) lithium-ion batteries.

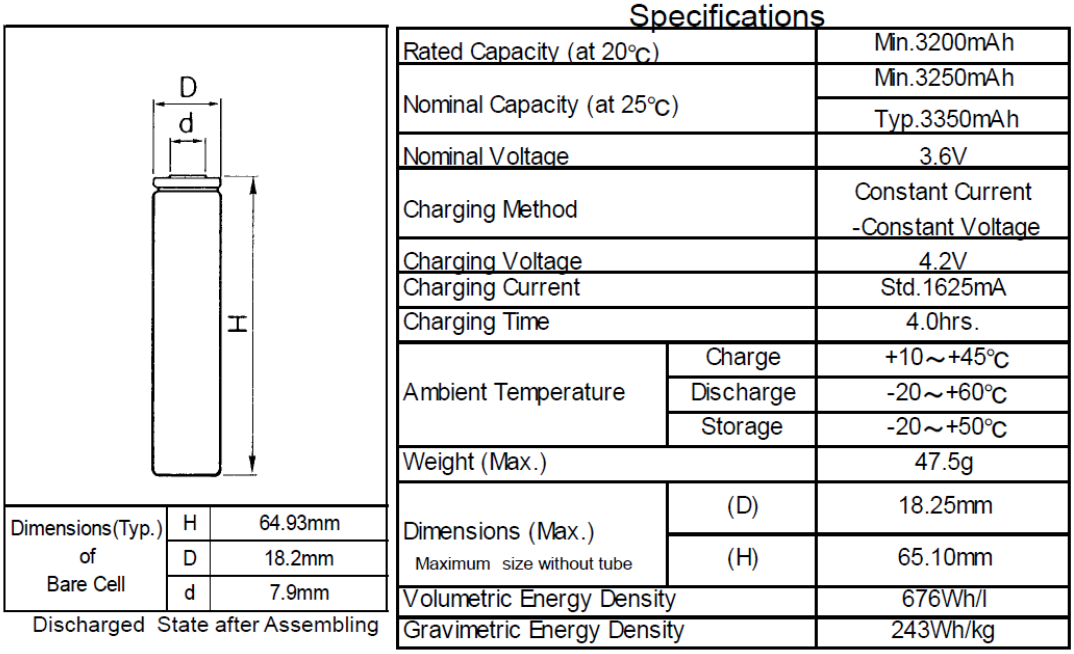


Figure 4.193: Specification of the Panasonic NRC18650 battery

Cell type	Manufacturer	Nominal V	Capacity Ah	Weight g	Temp. Range °C	Specific energy Wh/kg	Energy density Wh/L	Specific power W/kg	Cycle life cycles	Comments
LiAlMn oxide with LTO	Altair nano	24	60	2740	-40 to 55	52	106	~800	>16000	Available as a module, data taken from an evaluation specification sheet. Cycle life to 80% balance of life (BOL) capacity at 2C charge discharge with 100% DOD at 25°C. Calendar life of ~25 years. Can be recharged in ~15 min
$LiFePO_4$ and graphite	Lifebatt 2295130	3.3	18	550	-40 to 60	108	~210	>1300	2000-3000	This is a larger form factor prismatic cell. For 1s pulses, the specific power is >2600 Wkg. Maximum charge current is 90A, full charge in ~ 15 min
Li Mn and NMC	Molicell IBR18650BC	3.6	1.5	45	-30 to 60	129	326	~2100	750	Cycle life is to 80% BOL capacity for 20A discharge

										at 23°C, would be higher for lower discharge rates.
$LiCoO_2$ and graphite	Panasonic *UR18650Y*	3.7	2	43.3	-20 to 60	162	421	~300		Standard type of cell
$LiCoO_2$ and graphite	Panasonic *UR18650E*	3.6	2.15	44.5	-20 to 60	162	432	~500	>500	High power cell. Capacity ~85% of BOL at 500 cycles
Li NMC	Molicell *IHR18650BN*	3.6	2.2	45	-20 to 60	170	450	~700	>700	Cycle life is to 80% BOL capacity at 4 A and 23°C
$LiCoO_2$ and graphite	Panasonic *NCR18650*	3.6	2.25	45		180	~500	~1400	400	High power cell, cycle life I to 80% BOL
$LiCoO_2$ and NMC and	Molicell *ICR18650M*	3.7	2.8	50	-30 to 60	216	609	~300	>300	Capacity>90% of BOL after 300 cycles at 23°C
New Nickel Platform	Panasonic *NCR18650B*	3.6	3.35	47.5	-20 to 60	243	676	~450		High energy cell, highest specific energy in readily available cells
$LiCoO_2$ and tin-based	Sony *Nexelion WH1*	3.5	3.5	53.5		226	723		~300	Paucity of technical information available. Cells mostly used in Sony own laptops. Bare details in Chinese with Arabic numbers from: www.sony.com.cn/news_center/press_release/technology/1955_3787

Table 4.40: Some characteristics of commercially available secondary lithium-ion cell, ordered by specific energy [Underwater Technology, 33, 3, 2016]

There are several deficiencies of the present-day lithium-ion batteries that, if remedied with suitable ease and cost parameters, would enable superior lithium-ion batteries that could open new applications and expand the market for present ones. First, it is important to consider certain market factors that will have important ramifications on cost, material availability, and needed technology improvements to enable mass

production of different cell types and sizes. The market pull is strongly acting on lithium-ion battery manufacturers as application companies and governments around the world are asking for increased capacity and energy with a lower cost to fulfil the needs of greenhouse gas reductions through the implementation of electric vehicles of all types to replace petroleum and energy storage. So that intermittent renewable energy sources such as wind and solar can replace coal and natural gas fuels for energy production. The cost element is particularly important, for example, for motive power applications, e.g. for plug-in hybrid vehicles (PHEV) and battery electric vehicles (BEV).Recent estimates place the cost of producing lithium-ion cells is as low as $145 per kWh and the cost of a battery pack as low as $190 per kWh. *[http://www.greencarreports.com/news/1103667_electric-car-battery-costs-tesla-190-per-kwh-for-pack-gm-145-for-cells.]*

The second area of major production possibility is that of energy storage in connection with stabilization and storage for the electric grid. This area is driven as much by the requirements of government regulations and incentives to enable renewable energy sources such as solar and wind generation, which are inherently intermittent, to fit the demands of electrical utility producers and users. Besides, the cost is a very important driver for use of lithium-ion, but some applications such as frequency stabilization are not as cost-sensitive. If lithium-ion batteries are adopted for these applications, great demands will be placed on the availability of materials, especially lithium carbonate. To consider the likelihood of specific energy improvements in lithium-ion batteries we need to consider the limitations that exist now [Source: G. E. Blomgren, J. Electrochem. Soc., 2017, 164, 1, A5019]. Table 4.41 gives a picture of the main deficiencies and possible remedies as the author perceives them.

Location of Deficiency	Deficiency	Possible remedy
Carbonaceous anode (negative electrode)	Low capacity (Ah/kg, Ah/L)	Replace carbon with improved alloy anode that allows high coulombic efficiency, good power capability, low irreversible capacity, and low cost with little or no loss of specific capacity or cell voltage
Negative electrode-electrolyte interface	Low coulombic efficiency with ally anodes caused by solid electrolyte interphase (SEI) growth on first cycle and continuing with cycling	Improved coatings, functional binders and/or electrolyte additives to protect the interface during large volume changes
Positive electrode (lithiated transition metal oxide or phosphate)	Low capacity (Ah/kg, Ah/L) and charging voltage limit	Replace with new cathode material that allows high coulombic efficiency, good power capability, low irreversible capacity, and lower cost with little or no loss of capacity density or cell voltage
Positive electrode-electrolyte interface	Low coulombic efficiency at higher voltage limiting specific capacity and cycle life and causing increased cell impedance with cycling	Improve coating of cathode material, binders and/or electrolyte additives that can prevent impedance increase with cycling, dissolution of transition metal ions

Location of Deficiency	Deficiency	Possible remedy
Separator	Penetration with conductive particles or lithium dendrites	Improved coatings of separators that do not impede ion flux, salt diffusion or fluid flow, but can improve penetration strength or combine chemically with lithium dendrites
Metal collectors	Solid metalfoils add to cost and take away from energy as they are inert in the system, yet must be thick enough to provide adequate electrical and thermal conductance	Perforated or expanded metal collector are in common use for primary lithium batteries and secondary aqueous batteries, but have not been engineered for lithium ion

Table 4.41: Deficiencies of present lithium ion batteries and possible remedies [Source: G. E. Blomgren, J. Electrochem. Soc., 2017, 164, 1, A5019]

Evolutionary Progress up-to-2050- Battery

The history of lithium batteries is not that old, in contrast to fuel cells that have been described by Grove the first time in 1839. In the last 40 years, two new battery systems, Li-Ion and Ni/MeH, have not only dominated the portable electronics business but in many ways enabled it. They are now beginning to do the same for transportation, and Li-Ion has entered the electric grid market.

These advances have all been based on the concept of intercalation reactions. Now, the question that arises is how much further can intercalation chemistry be pushed? At a minimum, these cells will almost certainly displace Ni/Cd in consumer applications, as cadmium-based cells are banned from sale. There is still much room for improvement in the storage capability of Li-Íon cells.

- There is much dead weight and volume in today's batteries and supercapacitors.Also, the full capability of the active materials has not been attained. For example, the volumetric energy density of Li-ion batteries has increased from 250 to 680 Wh/L over the last decade.
- There is no reason to believe that the energy density can´t be further increased, possibly even as far as 50% on both volumetric and gravimetric basis within the next ten years. For almost all applications, the volumetric energy density is much more important than the gravimetric one.

However, further improvements will need significant changes in the materials used. One measure is to switch from lithium to magnesium. However, much effort will be needed to make a successful magnesium battery, including an anode, an electrolyte but most importantly a high-energy cathode. The beginnings of such cells will be accomplished within ten years, but without significant breakthroughs, it will probably not go commercial until 2030. Within ten years, the carbon electrode will have been replaced by metal alloy systems, perhaps tin or silicon-based. There is a finite probability that pure metals will be used in some liquid electrolyte cells by 2030. They find application today in all solid-state thin-film cells.

Related to conversion reactions isthe chemistry involved in metal-air and metal sulphur systems. The ambient temperature Li/S battery has been under development for more than a decade by e.g. *Sion Power* and *Oxis Energy*. Some cells are commercial and are used in some military markets for flight power today *[SionPower, Lithium Sulfur Batteries, 2012. [Online]. Available: http://www.sionpower.com/.]*.They already

substantially exceed the gravimetric energy storage capability of Li-ion but have a much lower volumetric storage capability.

It is important to keep in mind that energy storage devices, like batteries, capacitors have an upper limit to their storage capabilities, and this can be readily calculated. Today, depending on cell chemistry, less than 20% of the theoretical volumetric capacity got out of a battery so there is room for improvement in the engineering of the system as well as in the use of new materials and reactions.

If the demand to get more energy out of a system at the same power rating, then flow batteries or fuel cells are recommended alternatively in which the tanks of the reactants are increased while keeping the electrochemical cell itself at the same size. The use of photovoltaics or wind power will require much more energy storage capabilities, probably at the local level as well as centrally.

Low-cost sealed metaloxygen or metal–sulphur will probably have advanced to gain a significant market share. Intercalation-based batteries will retain a significant fraction of the market but will have switched to non-lithium-based electrochemistry, as there are predictions that it is almost certainly not enough lithium in the world to provide for transportation, grid storage, and home/office storage. Lithium could be replaced by magnesium, or if suitable electrodes can be found, sodium; zinc is not out of the question, but its storage capability is much lower because of the low cell voltage, ~1.5 V, compared to the 4 V for lithium-based cell systems.

For safety, it is likely that the sodium will be contained in some other host material, because the low melting point of sodium, around 100 °C, makes the possibility of thermal runaway too hazardous. Supercapacitors possibly will have morphed into batteries (hybrid-battery-capacitor), with the consumer having the opportunity to buy the desired battery that can supply electric energy from 90% power-intensive to 90% energy-intensive.

The final word on the degree of penetration of energy storage in the transportation and grid sectors will be determined by legal provisions, but technology can win out if all else is equal.

Possible or predictable breakthroughs – Battery

a. Improvement of Energy density
    - Development of Li/Sulphur Cell (→2025)
    - Replacement of Graphite with silicon (→2020)
    - Replacement of Graphite with lithium (→2020)
    - Development of metal/air cells (→2030)
    - Development of high voltage/capacity cathode (→2025)
b. Improvement of Power density
    - The increase of operating temperature (→ 2025)
    - Development of Nano-carbon additives (→2025)
c. Improvement of Safety
    - Employ hardly inflammable electrolytes based on ionic liquids, polymers or glass (→2025)
d. Decrease material costs
    - Reduce use or entirely replace cobalt with low cost material (→2025)

Identification of Gaps / Risks – Battery

a. The required power and energy density of the battery-system is too low;
b. The required temperature operating range for demanding climatic conditions is too narrow;
c. A sufficient charging infrastructure can´t be build-up for fast charging;

d. The investment cost and operating costs are too high comparing state of the art.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACAREChallenge 3 Goal 10** "Emissions Free Taxiing at Airports" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.194 grounding on the results of the 1st/2nd year PARE reports (PARE D1.1, 2018 and PARE D1.2, 2019).

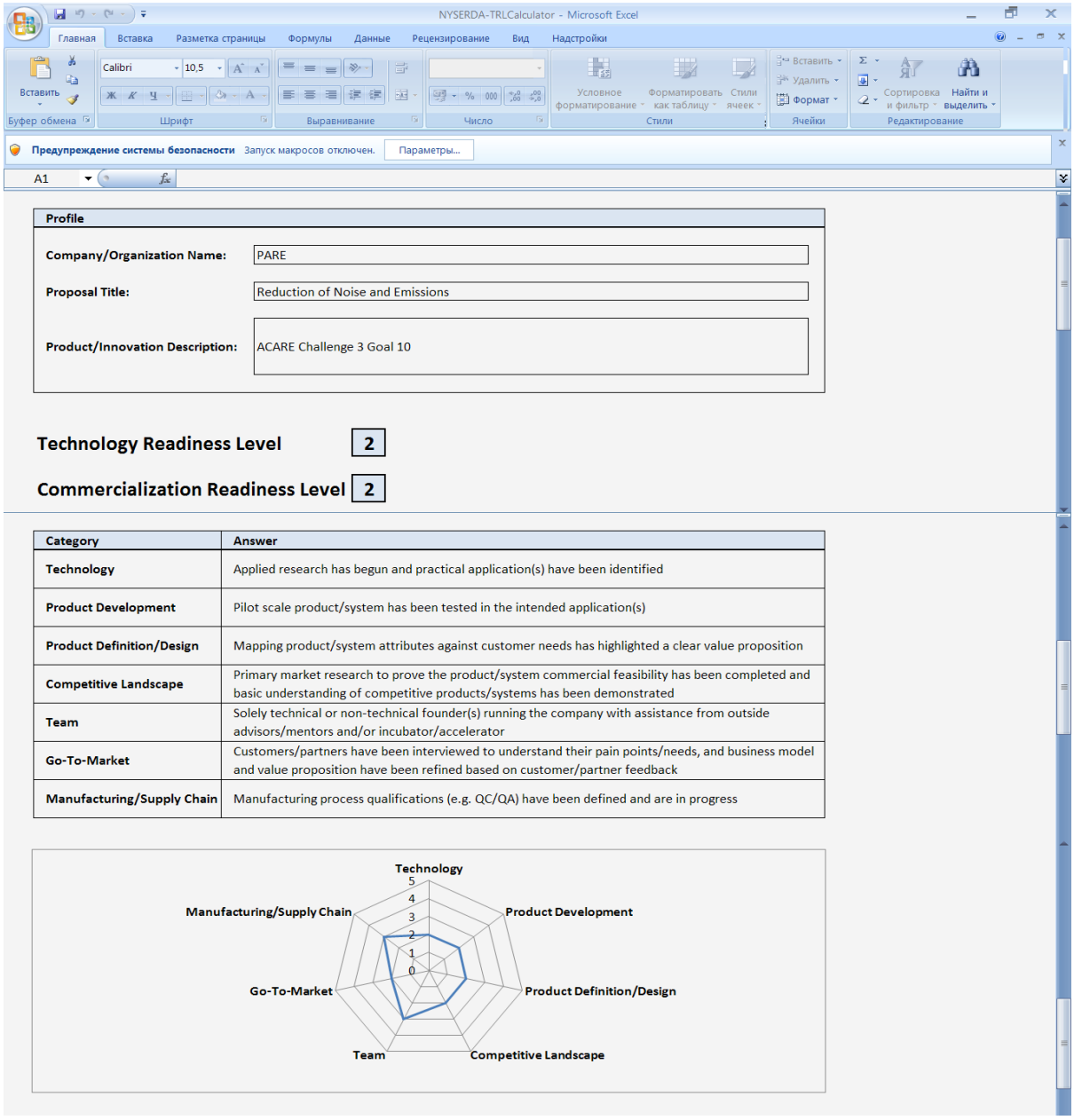


Figure 4.194: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 10 "Emissions Free Taxiing at Airports"

4.3 Design and manufacture bearing in mind recycling

**Flightpath 2050 goal 11: "Air vehicles are designed and manufactured to be recyclable*

Moving forward, aircraft recycling is becoming even more important, with 12,000 aircraft due to retire in the next 20 years. The industry is pursuing two parallel goals: a more streamlined recycling process to deal with current aircraft and a more holistic design for future aircraft, to account for what happens to a plane after it

has served its purpose. Recycling of aircraft parts depends mostly on the materials used and also on the fabrication process. The choice of materials for an aircraft is subject to a considerable set of constraints related to performance, weight, availability, cost, ease of manufacture and maintenance, durability and resistance to hostile environments. Adding the recycling ability is an additional constraint which can bring benefits in several of other areas; it may require consideration of materials not previously used in the aerospace industry and take advantage in the major progress made synthetizing new substances with tailor-made properties (graphene).

Currently, about 500 aeroplanes are disassembled annually. By 2030, that number is projected to be closer to 2,000 planes per year. The generation of aircraft being recycled today haven't been designed with their end-of-life in mind. And while the aircraft currently in production have more thought given to recyclability, there is still a long way to go before aircraft are truly sustainable. According to companies that store and disassemble planes, about 80% to 85% of an aircraft by weight can be recycled. The remaining portions end up in landfills.

An illuminating example of the experience and challenges of recycling is given by batteries (Key Topic T4.3).

KEY TOPIC T4.3 – Batteries for the More Electric Aircraft (MEA)

1) Requirements for Aircraft Grade Batteries

Competition in the aircraft industry market and global warming has driven the industry to think along economic and environmental lines. This has resulted in the emergence of a more electric aircraft (MEA) concept, providing for the utilization of electric power for all non-propulsive systems.

Traditionally these non-propulsive systems are driven by a combination of different secondary power sources such as hydraulic, pneumatic, mechanical and electrical. Recent technological advances in the field of power electronics, fault-tolerant architecture, electro-hydrostatic actuators, flight control systems, high-density electric motors, power generation and conversion systems have ushered the era of the *MEA*. This trend is accelerating, as aircraft manufacturers collaborate with their suppliers to design new systems and implement new electrical-intensive architectures. Adoption of the *MEA* concept is seen as a critical enabler for the aircraft industry to unlock significant improvements in terms of aircraft weight, fuel consumption, aircraft noise, total life cycle costs, maintainability and aircraft reliability.

The tremendous increase in the power demand of aircraft, especially in the last two decades, coupled with advancement in battery materials and technology has led to the development of many aircraft-grade battery systems with high energy density (more than 100 Wh/kg) and low-temperature capability with following key trades:

- To deliver power reliably and be certifiable safe
- To be lightweight
- To have a consistent power output over their operating environment
- To have a reasonably long life.

A small size, high energy density battery (Table 4.42) is the need of the aircraft industry as a 10kg decrease in the weight of aircraft will result in the saving of 17,000 tons of fuel and 54,000 tons of carbon dioxide emission per year for all air traffic worldwide. The reduction in battery weight is also profitable in terms of cost.[1]

[1] M.Tariq, A.I.Maswood, C. J. Gajanayake, A.K.Gupta, IET Electr. Syst. Transp., 2017, Vol. 7 Iss.2, pp 93-103

Serial no.	Criteria	Li-ion	Ni–Cd	Pb-acid
1	nominal cell voltage, V	3,20	1,20	2,00
2	typical battery cost in US$, (V, Ah, Wh)	207 (12, 21,252)	100 (12,20,240)	67 (12,20,240)
3	cost per Wh in US$	0.82	0.42	0.28
4	cycle life (no.)	3000	1500	250
5	cost per cycle in US$	0.069	0.067	0.268
6	cost per Wh per cycle in US$	0.00027	0.00028	0.00112
7	specific energy density, Wh / kg	135	65	40
8	operating temperature, °C	-20-60	-30-60	-20-60
9	self-discharge / month	2–3%	4–6%	15–20%
10	overcharge tolerance	very low	moderate	high
11	maintenance	not required	1–2 months	3–6 months

Table 4.42: Comparison of different cell chemistries used in aeronautics

2) Types of aircraft batteries

Only vented Pb-acid batteries were in use in aircraft until the 1950s. In the late 1950s, military aircraft started using vented Ni-Cd due to higher low-temperature capability, which was adopted by commercial aircraft. The use of alternative battery chemistries like Ag-Zn was discontinued because of high costs and poor reliability. From the late 1960s, the development of sealed Ni-Cd batteries, followed by sealed Pb-acid batteries in the late 1970s started for aircraft application, in which maintainability and reliability have been improved significantly. Ultra-low maintenance Ni-Cd batteries were developed by *SAFT* and *Marathon Norco* since the mid-80s, replacing the conventional vented Ni-Cd batteries.

The most common voltage rating for main aircraft batteries is 24V, as capacities are available between 23 and 75Ah. The number of batteries installed in the aircraft depends on the system architecture, e.g. the Airbus A380 has a complex architecture requiring three 24 V, 50 Ah Ni-Cd batteries. A fourth 50 Ah battery is dedicated to APU starting. The total weight of the batteries is about 210 kg.

The life duration of an aircraft battery depends on various factors such as tt number of operating hours, ambient temperature, start frequency and on-board charge. It is therefore difficult to determine in advance how long the expected life of a battery will be in the real situation. Typically, the life of Ni-Cd batteries on long-range transport jets is 6–9 years, while in commuter aircraft is 5–7 years. On the other hand, in military trainers and fighters, it is typically 4–6 years. By comparison, the life of Pb-acid batteries is half to one-third that of Ni–Cd.Though most of the civil aircraft have used Ni-Cd batteries, the trend is shifting (Table 4.43) towards Li-ion batteries with its tremendous opportunities to be employed in *MEA*.

Li-ion cells comprise sensitive electrochemistry which needs a detailed knowledge of its characteristics to allow its benefits to be exploited fully while ensuring maximum safety. We are likely to see further improvements in Li-ion performance as new electrode materials; electrolyte compositions and cell geometries are under research. Nanomaterials now being developed will also have a role to play. Nevertheless, Li-ion batteries are not currently envisaged as retrofit solutions, so Ni-Cd and Pb-acid batteries still have many years of work ahead of them.

Furthermore, many manufacturers include the Li-ion battery system with proper integrated battery management (BMS) and safety monitoring system, which are commercially available, e.g. the Li-ion battery with $LiFePO_4$-cell chemistry by *EaglePicher Technologies.*

Aviation Battery Manufacturer	Cell type	Function in the aircraft	Civil Aircraft	Ah
GS Yuasa (Japan)	Pb-acid	Main Aircraft		36
GS Yuasa	Li-ion		B-787	75
SAFT (France)	Ni-Cd	Main Aircraft, Auxiliary Power Unit (APU), a.s.o.	B-737, B-747, B-767, A320, A330, A340, A380, Bombardier, Gulfstream G650, ComacC919	23-53
SAFT	Li-ion		Airbus, Boeing	
SAFT	Ni-MeH	Emergency door, floor escape path lighting, electronic flight bags.		
ChanghongBattery (China)	Li-ion	Starting aircraft engine, DC emergency power supply	Airbus, Boeing	60
	Ni-Cd		Airbus, Boeing	
	Ag-Zn	Emergency starting power supply or on-board back up power supply	Airbus, Boeing, Tu-154	45
Concorde Battery (US)	Pb-acid		C-130, C-141	10-30
Concorde Battery	Ni-Cd		B-717	3,5
Hawker Energy Products Ltd (US)	Pb-acid			
Teledyne Battery Product (US)	Pb-acid			
Marathon Norco Aerospace (US)	Ni-Cd			75
EaglePicher (US)	Li-ion	Emergency Batteries (2006), Main Engine Start Battery for Light Jet(2010)	Honda Jet	30-65

EaglePicher	Ag-Zn			0.8-800
True Blue Power (US)	Li-ion	Starting aircraft engine	Robinson R44, Bell JetRanger helicopter	17-46
Acme Aerospace (US)	Ni-Cd	APU, Avionics, Environmental systems	B-777	47

Table 4.43: Details of batteries used in different aircraft

Most new batteries face the same adoption curve, starting with initial resistance and then acceptance.

3) Life Cycle Management – Recycling

In general, the same processes used to recycle automotive batteries are used to recycle aircraft batteries.[2]

A serious issue is related to the fact that the lithium battery market is in continuous evolution with the advent of many different new chemistries. Further, in addition to the rechargeable Li-ion batteries, also primary lithium batteries, using cathodes such as manganese oxide or thionyl and sulfuryl chloride, are still in the market and they may arrive at the recycling plant as well. Finally, also the electrolyte may widely change, passing from a variety of liquid organic solutions to polymer membranes. Clearly, this high diversity makes it difficult to develop a universally valid recycling process, as well as affecting its economics, since the new chemistries may not involve components worth being recovered.[3]

Indeed, the European Commission has mandated a Battery and Accumulator Directive, which imposes to the state members the following targets: [4]

- A 45% collection rate for waste-portable batteries to be met by 2016. A recycling efficiency to ensure that a high proportion of the weight of waste batteries is recycled, this including 65% of lead-acid, 75% of nickel-cadmium, and 50% of "other waste batteries," the latter likely referring to lithium batteries.

Considering the present low economic value, these targets can be met only if subsidies are provided, usually adding a tax to each manufactured battery, as indeed is the case. Under this scheme, battery recycling plants are now operating in Europe (e.g., *Batrec* in Switzerland, *Umicore* in Belgium, and *SNAM* and *Recupyl* in France) to honour the mandate.

Recycling plants are also in force under different schemes in the US (e.g., *Toxco*) and in Japan (e.g., *Sony* and *SumitomoMetal*). Due to the still scarce production of Li-ion batteries of EV types, the recycling is for the moment limited to the portable ones.

However, EV battery recycling is expected to gain quite a significant importance in the years to come.

4) Risks Related to (Li-ion) Batteries in Aircraft

Due to the use of certain chemical compounds in combination with high energy densities and the use of control electronics (potential of a technical defect) required for secondary batteries, Li-ion batteries are associated with specific potential hazards which need to be taken into special consideration concerning

[2]D. Vutetakis, The Avionics Handbook, 2001, Ch. 10, pp. 9

[3]B. Scrosati et. al, Advances in Battery Technologies for Electric Vehicles, Elsevier 2015: Recycling of Batteries possibly used in ground-vehicles or aircraft.

[4]http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key_waste_streams/batteries

safety. Spectacular incidents have raised public awareness of potential problems associated with Li-ion batteries.

- On 3 September 2010, UPS Airlines flight 6, a Boeing 747-400, crashed close to Dubai International Airport on its way to Cologne Bonn Airport, leaving two crew members dead. The crash had been caused by fire in the cargo area which contained lithium ion and lithium metal batteries.

- After a Boeing 787 coming from Japan had landed in Boston/US on 7 January 2013, fire broke out, caused by the thermal runaway of a Li-ion battery. As a consequence, the US-*Federal Aviation AgencyFAA* has mandated to install a casing for the battery to contain/extinguish the fire (Figure 4.195):

- On 12 July 2013, a non-rechargeable lithium metal battery in an ELT (emergency locator transmitter) of a Boeing 787 at London Heathrow Airport caught fire.



Figure 4.195: Boeing-787 relaunched the Li-ion battery system with the new design, adding an extra weight of 68 kg to the weight of the aeroplane

It is characteristic of a battery that it releases chemically stored energy in the form of electric energy in the course of the discharging process. In case of a "thermal runaway", the entire energy is not released as electrical energy in a controlled manner, but uncontrollably in the form of thermal energy. In case of such a failure, the thermal energy released by a lithium-ion battery maybe 7 to 11 times higher than the energy stored electrically. The produced heat accelerates the reaction, resulting in a critical overheating of the battery.

Besides, cathode materials may disintegrate at high temperatures. This reaction also produces heat (exothermic reaction) and releases bound oxygen; when a fire breaks out, the thus released oxygen makes it difficult to control the fire. It is even impossible to extinguish such a fire using conventional fire extinguishing methods.

Causes of battery fires:

- Improper handling;
- Mechanical damage;
- Secondary thermal stress;
- External short circuit, Internal short circuit caused by a cell failure or crash;
- Overcharge, Over-discharge and exhaustive discharge;
- Cooling system defect (large-scale batteries);
- Counterfeit lithium-ion batteries and chargers.

5) Threats Regarding Aircraft Batteries

5.1) Permanently installed batteries[5]

There are several potential threats that can be associated with aircraft batteries (Figure 4.196), their distribution networks and their charging and monitoring systems:



Figure 4.196: Use of batteries in a typical aircraft

- Battery Leakage. Overfilling a wet cell battery can cause leakage. Likewise, damage to the battery case caused by mishandling, overcharging or freezing can result in leakage.
- Battery Internal Failure or Short Circuit. Manufacturing defects or inappropriate handling can result in internal failures.
- Battery Overcharging. Batteries can be overcharged due to faulty charging equipment or inappropriate maintenance practices.
- Excessive Battery Charging/ Discharging Rate. Some battery types are vulnerable to high rates of charge or discharge.
- Battery Bus Fault or Fire. A Battery Bus Bar is "hot" - it cannot be electrically isolated from the source battery without physically removing the battery. [6]

As a consequence, the following preventive measures should be undertaken:

- Containment of thermal effect;
- High standard electronic protection against overheat (overcurrent, overvoltage, short circuits);
- The specific choice of battery structural material and design;
- Battery management system with a cooling system;
- Mitigation of pressure release effect;
- Venting areas within the battery/module;
- Specific venting outside the battery/aircraft when relevant;
- High robustness to shocks (handling) and ageing;
- Adequate integration in the Aircraft.

[5]Airbus, 18th Flight safety conference Berlin, 19-22 March 2012

[6]https://www.skybrary.aero/index.php/Aircraft_Batteries

5.2) Li-ion batteries in the cabin[7]

By accident of intentionally triggered thermal runaway of Li-ion cells occur due to devices carried by passengers in an aircraft cabin (Figure 4.197).



Figure 4.197: Batteries in the cabin of an airliner

5.3) Li-ion batteries in the cargo area

Batteries in cargo cabin can cause safety risks also, Figure 4.198.

Shipping lithium batteries have also caused havoc in the airline cargo industry. In the last years, the *U.S. Postal Service* banned the shipment of lithium batteries until the ruling was reversed in November. *Cathay Pacific* and *British Airways* recently discussed banning the shipment of any related Li-ion battery devices in their cargo holds.

There is so much concern in the industry over onboard fires related to lithium-ion that the *FAA* released a Safety Alert for Operators dated Oct. 8, 2010. The title is "Risks in Transporting Lithium Batteries in Cargo by Aircraft."

Furthermore, cargo areas are not accessible for direct firefighting and *Halon 1301*, used as a fire extinguishing agent in cargo holds or engines, is insufficient to stop the thermal runaway and prevent propagation to adjacent cells.

Recycling of aircraft parts depends mostly on the materials used and also on the fabrication process. The choice of materials for an aircraft is subject to a considerable set of constraints related to performance, weight, availability, cost, ease of manufacture and maintenance, durability and resistance to hostile environments. Adding the recycling ability is an additional constraint which can bring benefits in several of other areas; it may require consideration of materials not previously used in the aerospace industry and take advantage in the major progress made synthetizing new substances with tailor-made properties (graphene). There is a need for effective materials extraction and separation technologies, worthwhile end-use

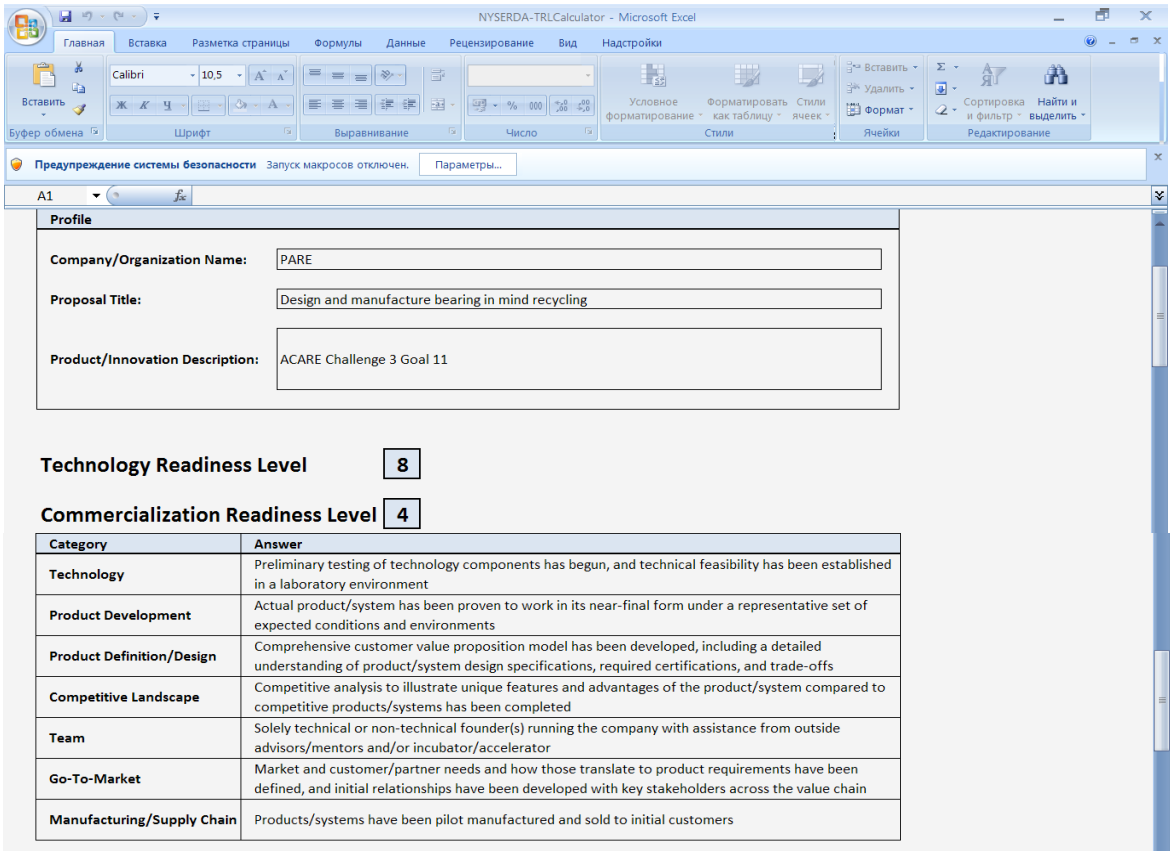
[7]Airbus, 18th Flight safety conference Berlin, 19-22 March 2012

applications for the recovered materials as well as an attractive business model for aircraft recyclers. Only when all of these conditions are united can the aircraft recycling industry truly take off in Europe.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 11** "Design and manufacture bearing in mind recycling" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.199 grounding on the results of the 1st / 2nd year PARE reports (PARE D1.1, 2018, PARE D1.2, 2019).



Figure 4.198: Cargo with batteries that can cause safety risks



Profile	
Company/Organization Name:	PARE
Proposal Title:	Design and manufacture bearing in mind recycling
Product/Innovation Description:	ACARE Challenge 3 Goal 11

Technology Readiness Level 8

Commercialization Readiness Level 4

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Actual product/system has been proven to work in its near-final form under a representative set of expected conditions and environments
Product Definition/Design	Comprehensive customer value proposition model has been developed, including a detailed understanding of product/system design specifications, required certifications, and trade-offs
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Solely technical or non-technical founder(s) running the company with assistance from outside advisors/mentors and/or incubator/accelerator
Go-To-Market	Market and customer/partner needs and how those translate to product requirements have been defined, and initial relationships have been developed with key stakeholders across the value chain
Manufacturing/Supply Chain	Products/systems have been pilot manufactured and sold to initial customers

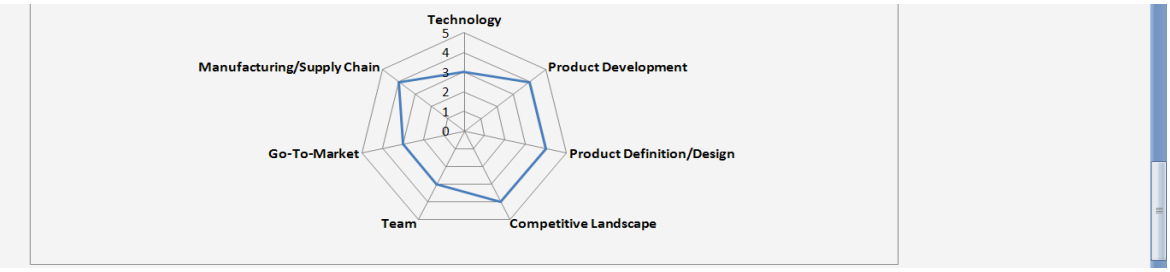


Figure 4.199: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 11 "Design and manufacture bearing in mind recycling"

4.4 Sustainable Alternative Fuel Sources

**Flightpath 2050 goal 12: "Europe is established as a centre of excellence for sustainable alternative fuels, including those for aviation, based on a strong European energy policy.*

The supply of fuel alternative to kerosene is subject to major efforts by large consumers like the U.S. Air Force. The consumer base is more diversified in the airline industry, but it is no less important due to a large number of flight hours. Although airlines have been willing to test new fuels a coordinated effort must be done far upstream to: (i) consider a variety of sources of fuel, that do not interfere with food production and whose environmental impact is neutral or positive (waste disposal); (ii) establish the technical feasibility to meet all applicable quality and safety standards and certification requirements; (iii) assess the economic and environmental feasibility of large-scale sustained production, distribution and use.

For example, hydrogen is a clean fuel that produces only water vapour by combustion. However, the quantities produced, and altitudes should be considered as for contrails. Hydrogen has a low volume power density and requires cryogenic conditions; water is an abundant source of hydrogen but its separation by hydrolysis is energy consuming. At the opposite extreme, some algae have high yields per unit area of culture; the full processing chain up to flight grade fuel needs to be considered. In between other options exist, making multiple sources of aviation fuel all the more desirable.

The Key Topic (T4.4) is thus the availability and sustainability of alternative fuel sources.

KEY TOPIC T4.4 – Sustainable Alternative Fuel Sources

The European Commission, Airbus, and high-level representatives of the Aviation and Biofuel producers' industries, launched in 2011 the European Advanced Biofuels Flightpath. This action is scheduled to achieve 2 million tons of sustainable biofuels used in the EU civil aviation sector by the year 2020. The overview of objectives, tasks, and milestones of this Flight Path[8] is shown in Table 4.44.

The supply of fuel alternative to kerosene is subject to major efforts by large consumers like the U.S. Air Force. The consumer base is more diversified in the airline industry, but it is no less important due to a large number of flight hours. Although airlines have been willing to test new fuels a coordinated effort must be done far upstream to: (i) consider a variety of sources of fuel, that do not interfere with food production and whose environmental impact is neutral or positive (waste disposal); (ii) establish the technical feasibility to meet all applicable quality and safety standards and certification requirements; (iii) assess the economic and environmental feasibility of large-scale sustained production, distribution and use.

For example, hydrogen is a clean fuel that produces only water vapour by combustion. However, the quantities produced, and altitudes should be considered as for contrails. Hydrogen has a low volume power density and requires cryogenic conditions; water is an abundant source of hydrogen but its separation by

[8] (https://ec.europa.eu/energy/sites/ener/files/20110622_biofuels_flight_path_launch.pdf).

hydrolysis is energy consuming. At the opposite extreme, some algae have high yields per unit area of culture; the full processing chain up to flight grade fuel needs to be considered. In between other options exist, making multiple sources of aviation fuel all the more desirable.

Searching fuels alternative to kerosene is a subject of main efforts of the large consumers, such as USA Air Forces. The customer base is more diversified in the airlines' industry, but it is no less important due to the great number of flight hours. Although the airlines are ready to test the new fuel types, coordinated efforts shall be in advance undertaken, in order to:

1. Examine the variety of alternative fuels sources that are not intersected with food production, and the environmental effects of which are neutral or positive (elimination of waste).
2. Determine the technical feasibility of complying with all existing quality and safety standards and certification requirements.
3. Appraise the economicand environmental feasibility study of large-scale stable production, distribution and consumption.

Time horizons	Action	Aim/Result
Short-term (next 0-3 years)	Announcement of action at International Paris Air Show	To mobilise all stakeholders including Member States.
	High level workshop with financial institutions to address funding mechanisms.	To agree on a "Biofuel in Aviation Fund".
	> 1,000 tons of Fisher-Tropsch biofuel become available.	Verification of Fisher-Tropsch product quality. Significant volumes of synthetic biofuel become available for flight testing.
	Production of aviation class biofuels in the hydrotreated vegetable oil (HVO) plants from sustainable feedstock	Regular testing and eventually few regular flights with HVO biofuels from sustainable feedstock.
	Secure public and private financial and legislative mechanisms for industrial second generation biofuel plants.	To provide the financial means for investing in first of a kind plants and to permit use of aviation biofuel at economically acceptable conditions.
	Biofuel purchase agreement signed between aviation sector and biofuel producers.	To ensure a market for aviation biofuel production and facilitate investment in industrial 2nd generation biofuel (2G) plants.
	Start construction of the first series of 2G plants.	Plants are operational by 2015-16.
	Identification of refineries & blenders which will take part in the first phase of the action.	Mobilise fuel suppliers and logistics along the supply chain.
Mid-term (4-7 years)	2000 tons of algal oils are becoming available.	First quantities of algal oils are used to produce aviation fuels.
	Supply of 1.0 M tons of hydrotreated sustainable oils and 0.2 tons of synthetic aviation biofuels in the aviation market.	1.2 M tons of biofuels are blended with kerosene.
	Start construction of the second series of 2G plants including algal biofuels and pyrolytic oils from residues.	Operational by 2020.
Long-term (up to 2020)	Supply of an additional 0.8 M tons of aviation biofuels based on synthetic biofuels, pyrolytic oils and algal biofuels.	2.0 M tons of biofuels are blended with kerosene.
	Further supply of biofuels for aviation, biofuels are used in most EU airports.	Commercialisation of aviation biofuels is achieved.

Table 4.44: Objectives, tasks, and milestones of European Advanced Biofuels Flightpath

For example, the hydrogen is a pollution-free fuel, during combustion of which only aqueous vapour is produced. However, the quantity of vapour generation and the altitudes concerning the appearance of condensation trails shall be taken into account. The hydrogen has a low power-to-weight ratio and requires cryogenic conditions; the water is an inexhaustible source of hydrogen, but its release from the water byhydrolysis requires lots of energy. The opposite extreme – some algae provide high output of production per cultivation unit area. It is necessary to consider the complete processing chain until deriving usable aviation fuel. Between these two extremes, there are other variants of provisioning aviation fuel sources, much more preferable.

The alternative types of fuels for aviation with less carbon intensity have been considered by many countries, both from the viewpoint of potential usefulness for the environment and delivery safety precautions [Kahn Ribeiro S., et al., 2007]. The alternative types of fuels are also a subject of ICAO's attention. In the Conference regarding the aviation and the alternative types of fuels (CAAF) 2009 a global base was established for developing the alternative types of fuels. The examples of fuels alternative to the traditional jet fuel (mineral kerosene), that were investigated in the effort [Grote M., Williams I., Preston J., 2014] are as follows:

– liquefied hydrogen (LH_2);

– methane;

– methanol;

– ethyl alcohol, ethanol;

– biodiesel (dimethyl ethers) based on retreatment of vegetable oils and fats;

– atomic energy;

– synthetical paraffine kerosene (SPK);

– Fischere-Tropsch (F-T) process, based on the retreatment of raw materials, such as biomass, natural gas or coal;

– hydrotreating (includinghydrogenation, hydro-cracking and hydraulic cleaning, especially within the framework of oil refining) of vegetable oils and fats with hydraulically treated renewable reagent (HRJ). Sometimes the renewable reagent is referred to as bio-SPK or hydro retreated compound ethers and fatty acids (HEFA).

As it was found, the majority of variants from this list at present are not suitable for different reasons: heavy expenses, absence of infrastructure for fuel production and delivery, increased fuel tanks requiring greater fuselage volumes, which results in increase of the weight and the resistance, low energy density, safety problems [Lee, D.S., et al., 2010; Allen, C., et al., 2012; FAA, 2011].

Taking into consideration the growing ecological and energyproblems during the last decade, the aviation industry has involved significant resources for developing stable alternative types of fuel that may promote the achievement of coordinated political objectives oriented to the diversification of electrical power supply, agriculture support and combating climate change.

The International Committee on fuel specification has developed a standard process [ASTM International, 2014], in order to check the suitability of the stable alternative types of fuels taking into account the requirements of existing systems and infrastructures. As a result, at the present, three ways of alternative fuel production are approved for using in commercial aviation, and they are included in the new alternative fuel standard [ASTM International, 2015]. Among these are:

– fuel based on the hydraulic treatment of vegetable oils and animal fats, such as hydrotreated compound ethers and fatty acids / hydrotreated vegetable oils (HEFA / HVO);

– Fischere-Tropsch fuel derived from biomass (the biomass down to BTL liquid);

– synthetic alisoparaffin fuels derived from sugars.

The first two fuels are approved for blending with traditional jet fuel in proportion up to 50 %, whereas the blending proportions of the synthetical isoparaffins are limited to 10 %.

On the short-term horizon, it can be provided more quantity of biofuel for aviation if the biodiesel will receive authorization for application in aviation. In spite of the fact that the biodiesel does not apply with the aviation requirements and requires further treatment for producing equivalent jet fuel, it can be potentially used in aviation in case of low blending proportions (till 10 %) with conventional jet fuel [EASA, EEA, EUROCONTROL, 2016].

Meanwhile, in connection with the expected oil price growth, ecologic requirement strengthening regarding the noxious emissions, as well as the eagerness to decrease the dependency on oil, the civil aviation in the developed countries directs its look to the alternative types of fuels.

The leading aircraft producers and airlines in these countries have already made a bid for biofuel, which it seems practical to be produced from different sorts of biomass and organic residues (look in Chapter 4.1.5 about SAF and CORSIA, in the European emission trading system ETS the CO_2 originating from burning the ecologically friendly biofuels was not taken into account). The advantages of the aviation biofuel are the fact that its application is not related to changes in the existing engines and the fuel infrastructure. The carbon dioxide escaped in the course of burning is compensated by the quantity of carbon dioxide absorbed by the biomass from the atmosphere during vegetation. However, the energy expenditure for growing, transportation and processing of the biomass decreases this effect. Besides that, the expenditure of freshwater and agriculturally used areas for producing biofuel at a time when the best part of the global population faces the problems with food provision draws criticism. Nevertheless, the effect of compensating the carbon dioxide emissions at the expense of using the second-generation biofuels can make up 80 %. The International Air Transport Association (IATA) puts forward an objective of reaching the ratio of using the new generation biofuels in 2020 at the level of 6 %.

The western certification centres have approved the method of producing aviation kerosene from biomass (biomass-to-liquid) using the Fischere-Tropsch process, and later the method of producing biofuel from vegetable oil was approved. Under consideration are also other processes, by means of which production of biofuel is possible. Such a certification allows for airlines using biofuels on passenger flights in proportion with the conventional kerosene up to 50 %.

Already more than 1600 passenger flights with the use of biofuels (a mixture of biofuel and conventional kerosene) have taken place in the world. It can be expected that within the forecast period the developed countries will actively promote the implementation of biofuels in the aviation industry using sometimes provocative and forbidden financial mechanisms. The systems of emission trading will gain widespread. Thanks to these tools it will be possible to bring down the price of biofuel in comparison with the traditional fuel.

The hydrogen is also considered as an advanced alternative energy source for the aviation industry. It has thrice bigger energetic potential than the kerosene, however, even in the liquid state, it requires four times greater volume than the kerosene. In the process of its firing into the engine, the CO_2 is not generated, as well the NO_x emissions decrease. Also, it can be used in fuel cells for generating electric energy on the aircraft board. The problems of using the hydrogen as an aviation fuel are related, on the one hand, with technological difficulties during its transportation and storage, and on the other hand, with energy consumption of its production. The mass production of hydrogen, including in liquid state, is possible by using nuclear power engineering (in the future - thermonuclear reaction). It is expected that within the forecast period the

hydrogen will not obtain a wide circulation in the aviation industry. However, the hydrogen is justifiably considered as an energy carrier of the future.

For some regions of Russia of current interest is the use of aviation condensed fuel that is produced from the oil-dissolved gas. Those are the regions where the substantial stocks of condensed fuel up to now are fired in torches on the oil deposits. Using this fuel will permit to solve the problem of securing aviation fuel into the outlying northern regions of the country. According to the program "Energy strategy – 2030" the maximally complete utilization and saving of the oil-dissolved gas resources is one of the strategic objectives of the oil complex industry. The strategy foresees that as late as at the end of the first stage of its realization 95 % of the extracted oil-dissolved gas will be efficiently used.

The Rolls-Royce Company carries out active investigations for evaluating theeconomically viable alternative types of fuels. In February 2008 R-R has joined with Airbus and Shell for testing the A380 aircraft flying with 40/60 mixture of GTL and kerosene (the GTL or gas-liquid) is are duction process of converting the natural gas or other gaseous hydrocarbons into more heavy hydrocarbons. The gases enriched with methane are converted to liquid fuel through the synthesis gas ($CO+H_2$) as an intermediate product by using the Fischere-Tropsch process. Using this line route, some of the gaseous wastes of theoil-processing plants and oil-commercial fields can be converted to valuable fuel oils blended with kerosene. Otherwise, the excess gas would be discharged to the atmosphere thus adding energy to global warming. The activities involve testing biofuels based on the jatropha (jatropha – an oleaginous plant that is doing well in arid areas) on the Boeing 747-400 aircraft. Finally, British Airways proposed to the suppliers to deliver fuel for testing on the RB211 engine at the covered test bench. In these tests' evaluation of engine operation, processing and emissions for each type of fuel are carried out. There is little likelihood that the wide-scale replacement of the kerosene in aviation will be favourable in the next decade [Parker R., Lathoud M., 2010]. Within the AAFEX program framework the CFM56-2C1 engine emissions of NO_x and CO were determined depending on the type of fuel used:

- Standard fuel JP-8 (or base);
- Fischer-Tropsch (FT) fuel, synthesized from natural gas (FT1), Shell corporation;
- Fischer-Tropsch fuel produced from Sasol coal (FT2);
- A mixture of FT1 and FT2 fuels with JP-8 in proportion 50:50.

In Figure 4.200 the values of $EINO_x$ emissions (standardized to the fuel caloricity value) are shown, depending on fuel consumption and environment temperature.

The testing data suggest that the increase of the ambient temperature leads to an increase of the $EINO_x$ emissions for the power rating ≥ 30 %. The nature of $EINO_x$ emissions change with the ambient temperature increasing is the same for different types of fuels, and the $EINO_x$ emissions for the FT1 fuel were always lower than those for the JP-8 fuel.

On Figure 4.201, the EICO graphs are shown, depending on the fuel flow and the ambient temperature, for the ratings 4 %, 7 % and 30 % of nominal power.

According to the results of investigations [*NASA/TM–2011-217059*]:

– reduction of EICO by 10 % was achieved by using the FT1 fuel as regard to the JP-8 and FT2 fuels;

– the EICO emissions when using the FT1 fuel are lower than the emissions when using the JP-8 and FT2 fuels within the whole range of ambient temperatures investigated;

– the EICO ambient temperature dependence isforemost strong at the rating 4 % of nominal thrust and almost is absent (is within theconfidence error range of themeasuring equipment) for the ratings greater than 30 % of nominal thrust.

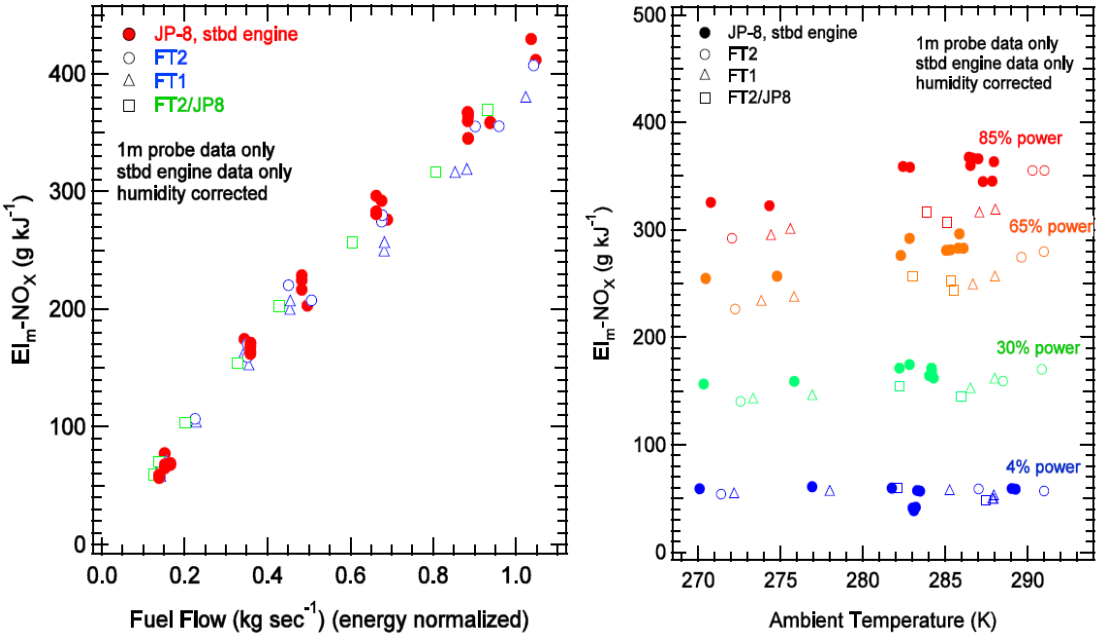


Figure 4.200: Results of investigations to the Alternative Aviation Fuel Experiment (AAFEX) program [*NASA/TM–2011-217059*]

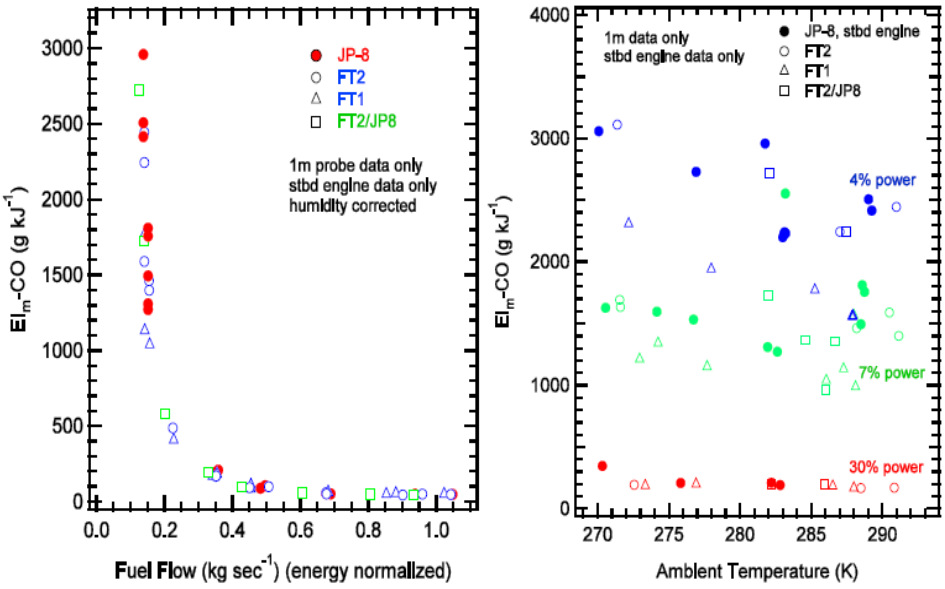


Figure 4.201: The results of investigations to the Alternative Aviation Fuel Experiment program (AAFEX) [*NASA/TM–2011-217059*]

On Figure 4.202 shown is the dependence of EINO$_x$emissions on the thrust rating of engine operation when using the base and alternative fuels, as well as shown are the NO$_x$ emissions measured during certification of the CFM56-2C1 engine that was carried out using the JET-A fuel.

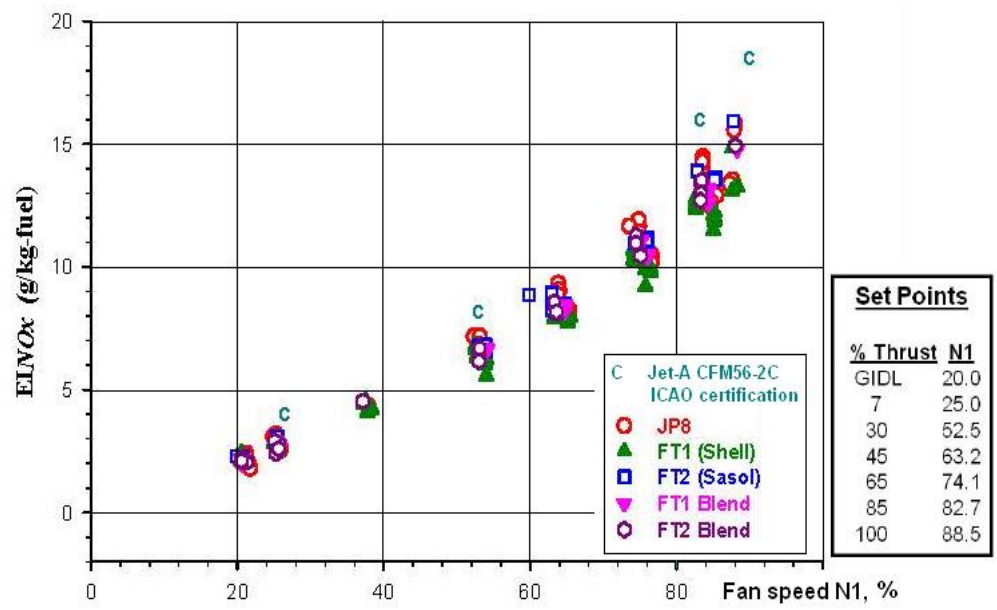


Figure 4.202: The results of strict policy investigations to the Alternative Aviation Fuel Experiment (AAFEX) program [*NASA/TM–2011-217059*]

The points "C" correspond to values obtained on the CFM56-2C engine during its ICAO certification [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/ 20110007202.pdf]. The reduction of NO_x by 5-10 %, achieved during carrying out investigations to the AAFEX program, is in line with two previous tests regarding the influence of the alternative FT fuels based on the natural gas on reduction of the NO_x и CO emissions: 1) Pratt & Whitney on the PW308 engine and 2) GE on the CFM56-7 engine.

For the PW308 engine operating at the rating of 85 % nominal thrust, the $EINO_x$ value was reduced approximately by 7 % for the FT fuel (Shell, natural gas) in reference to the JP-8. It is noted that the $EINO_x$ value at idle running is greater for the FT fuel tested on the PW308 engine, though the difference can becaused by the experimental errors. During testing the CFM56-7 engine the $EINO_x$ emissions were reduced by 11 % for the FT fuel (natural gas, Syntroleum) in reference to the Jet-A1.

The results of AAFEX tests indicate that one of the promising directions for decreasing the NO_x emissions is using the alternative fuels [*Alternative Aviation Fuel Experiment (AAFEX). Technical Report NASA/TM–2011-217059. Publication Date: Feb 01, 2011. - 408 p.*].

Predictive appraisals of accomplishment of the ecological objectives up to the year of 2050 (Figure 4.203) and the biofuel emissions over the operational lifetime are analyzed in the work [SWAFEA: A European study of the feasibility and impact of the introduction of alternative fuels inaviation // Philippe Novelli. - IOS Press, 2011. – pp 129-137. - DOI: 10.3233/978-1-61499-063-5-129]. As well, the price for biofuel is predicted (Figure 4.204).

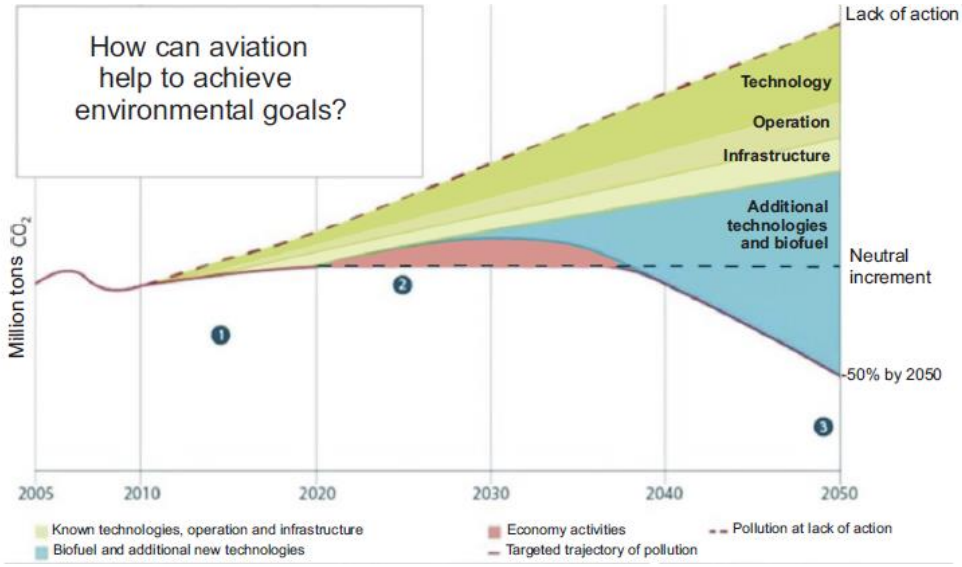


Figure 4.203: Predictive appraisal of accomplishing the ecological objectives 2050

At present, using biofuel in aviation is not of economic benefit because it is more expensive than the conventional aviation kerosene. As predicted by the experts, the oil prices can fall in already in the near future (Figure 4.204). This being the situation, one of the measures can be the legislative obligations to use in one or another proportion the purer, but simultaneously the more expensive alternative types of fuels. However, such measures will cause deterioration of the competitively of air transportation. According to Merrill Lynch' estimates, discontinuation of biofuel production will cause a rise in oil and benzine prices by 15 %. The incumbent China petroleum refining company Sinopec became a pioneer in creating this type of fuel from palm oil and recycled vegetable oil for food preparation, at the Zhenhai Refining and Chemical Company factory. The first evaluation flight of the China Eastern Airlines' Airbus A320 airliner with this type of fuel was carried out in April 2013.

Currently, the main problem in the way of biofuel commercial application is the biofuel price. The biofuel produced in accordance with the resource-recovery technologies throughout its life cycle reduces the carbon dioxide by 50-80% in comparison with the oil fuel, and therefore it will have a dominant role in supporting the aviation growth with simultaneous improvement of the ecological indices (Figure 4.205). According to Boeing's annual commercial aviation market forecast, for meeting the booming demand on internal and international passenger transportation at 2033 it will be necessary for China more than 6000 new aeroplanes. It is necessary also to be taken into account that the ecology movement and the introduction of EU ETS exert influence on the commercial aviation in terms of introducing, in the very near future, an additional ecological tax for the airlines.

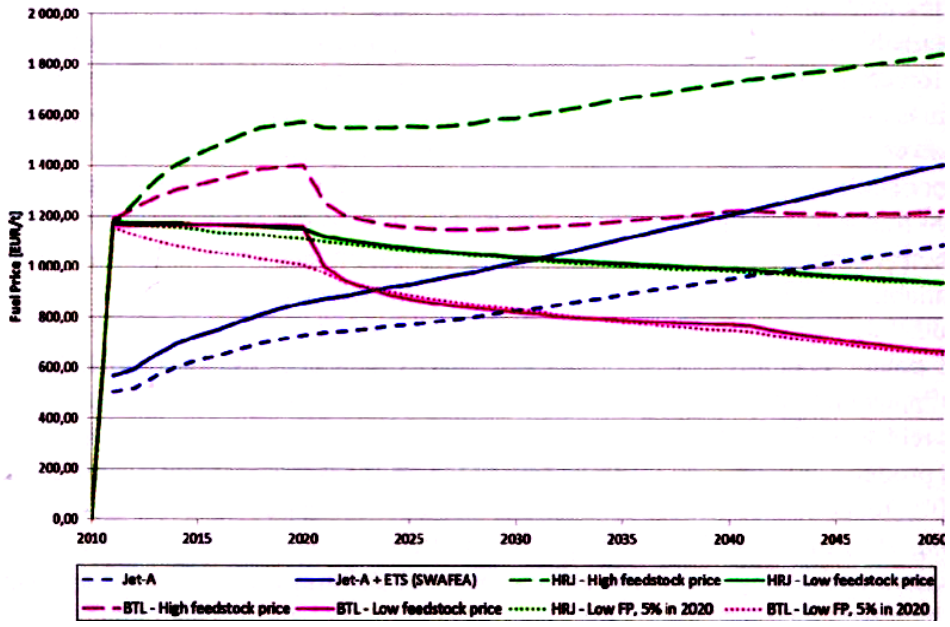


Figure 4.204: Biofuelprice forecast

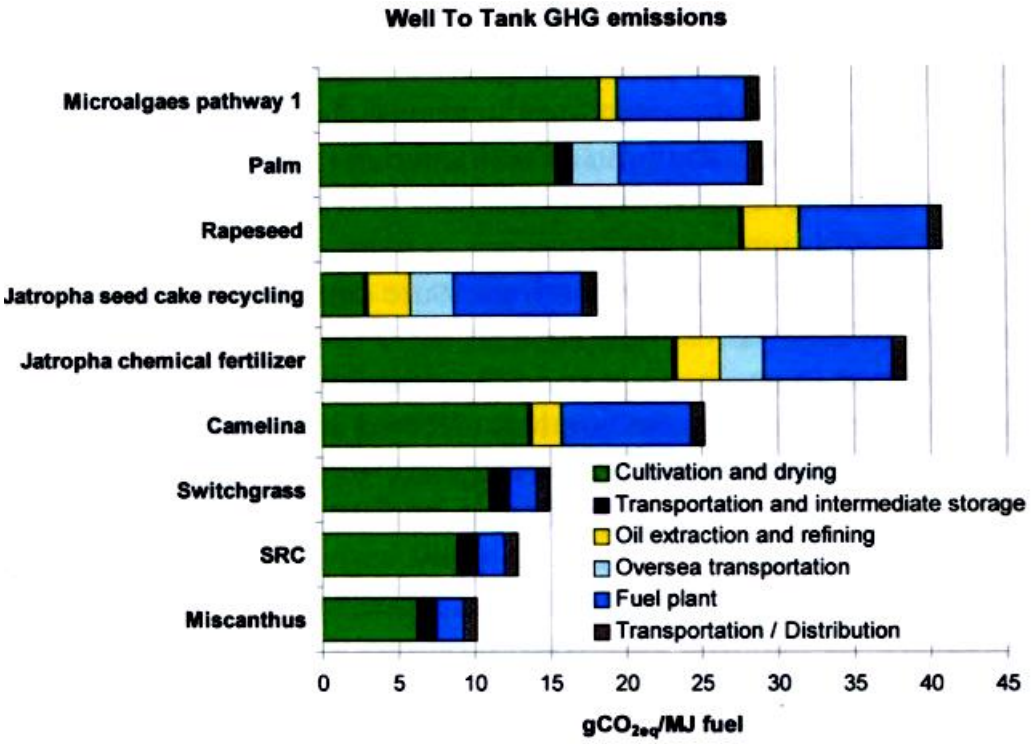


Figure 4.205: Biofuel emissions over the life cycle

Two main scenarios based on a possible change of the oil price are taken in consideration. In the first instance the price decreases, in the second, increases.

The first scenario supposes an extremely pessimistic forecast for using the biofuel, dismantling of investigations and reduction of areas used for growing appropriate agricultures. According to this scenario, if the fall in prices lasts long duration, the biofuel production can be ceased at all, and nothing will be said here about its any use. As prerequisites for such a scenario serve may the following: development of light tight oil

production technologies, entry into oil market of new producers from Africa, America and Asia, general curtailment on oil demand in other industry sectors, reduction of global economics, and other factors.

The second scenario is favourable for mastering the biofuel and widening its usage. However, there will be not an immediate growth of its consumption, since this requires significant changes in the technological infrastructure of commercial aviation, which can take place not immediately. As prerequisites for such a scenario serve may the following: the growth of global economics and international trade, reduction of oil production, cost reduction of biofuel production and a number of other reasons.

Possible alternative aviation fuels

BIOFUELS

In the initial 2011 Biofuel Flightpath document, only three candidates were considered, but by now several alternative biofuels are under scrutiny or already approved[9].

- Synthetic Fischer-Tropsch (FT) based kerosene produced through biomass gasification

Fischer-Tropsch synthesis entails a process which produces a gaseous mixture of hydrogen and carbon monoxide called syn-gas, over the surface of a catalyst material10. This is then converted into liquids of various hydrocarbon chain length and product distributions. These hydrocarbons can then be further processed into higher quality liquid fuels such as gasoline and diesel.

- Hydrogenated Esters and Fatty Acids (HEFA) and Hydrogenated

HEFA derived synthetic paraffinic kerosene is based on triglycerides and fatty acids which can originate from plant oils, animal fats, algae and microbial oil. Hydrogen demand for hydroprocessing of different feedstock qualities varies, resulting in conversion cost advantages for certain raw materials like palm oil and animal fats. HEFA production is already proven on a full commercial scale. Neste Oil operates two 190,000 t/a HEFA plants in Finland and one 800,000 t/a plant each in Singapore and Rotterdam. UOP and its customers have announced several HEFA projects worldwide. In Europe, both ENI and Galp Energia have plans for HEFA plants at 330,000t/a each, but these facilities are designed for diesel replacement in road transport and as such cannot be used for aviation unless some process modifications are carried out on the existing facilities.

- Pyrolysis Oils (HPO) produced from lignocellulosic biomass.

HPO is still at a research phase. It entangles developing fast pyrolysis processes. A few of them (e.g. Ensyn/Envergent Technologies (a joint venture between UOP and Ensyn Corp from Canada) and BTG in the Netherlands) are implementing the pyrolysis process on a commercial scale to produce crude pyrolysis oil. Pyrolysis oil, unlike vegetable oils (VO), contains a few hundred different chemical species. For application in the transport sector, the crude oil needs further upgrading to produce HPO. One or more hydrogenation steps are required to achieve the desired product quality. The scale of operation for producing the pyrolysis oil can be quite different from the upgrading activities. The latter one might be combined with current refinery operations. Envergent/UOP, for example, is conducting a demonstration project for Pyrolysis and the Upgrading technology to transport fuels at the Tesoro refinery in Hawaii. Contrary to FT and HEFA fuels HPO will still contain a certain number of aromatic compounds which are currently needed in jet fuel to avoid engine sealing problems. Therefore, HPO may complement HEFA and FT.

[9] https://ec.europa.eu/energy/sites/ener/files/20130911_a_performing_biofuels_supply_chain.pdf

[10] A. D. Surgenor, J. L. Klettlinger, C. H. Yen, and L.M. Nakley, "Alternative Fuel Research in Fischer-Tropsch Synthesis", https://ntrs.nasa.gov/search.jsp?R=20130000439 2017-11-17T11:23:50+00:00Z

➢ Alcohol to Jet (ATJ)

The alcohol to jet (ATJ) is characterised by the production of alcohols as an intermediate product derived from biomass as shown inFigure 4.206:

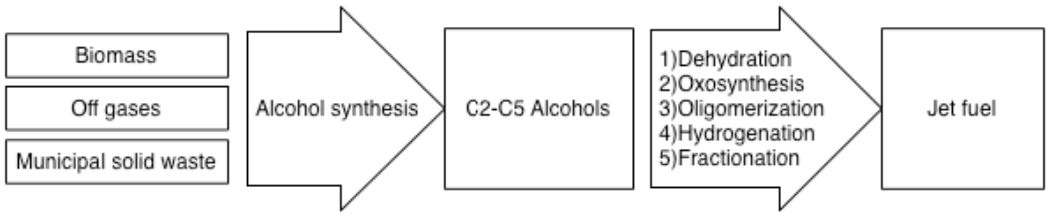


Figure 4.206: Possible pathways to obtain ATJ biofuel. Source "2 million tons per year: A performing biofuels supply chain for EU aviation - August 2013 Update http://ec.europa.eu/energy/technology/events/2011_05_18_biofuels_in_aviation_en.htm)

The overall process consists of alcohol synthesis from the raw materials followed by chemical synthesis into jet fuel. An advantage of ATJ technology is that it can be fully integrated with a wide variety of different front-end technologies for the production of alcohol intermediates. ATJ is currently still at pilot plant scale. Major players are Swedish Biofuels AB in Europe and Gevo in the United States. The technology called Direct Sugar to HydroCarbons, DSHC, developed by Amyris and Total, produces pure iso-paraffinic molecules by fermentation of any type of sugar, followed by mild hydrogenation. The first industrial molecule, a C15 hydrocarbon called farnesane, can be safely incorporated in fossil jet-fuel at 10% and ASTM certification is presently underway.

Advantages and limitations

ADVANTAGES

The most important motivations for biofuel usage concern the mitigation of climate change, the reduction of fossil fuel dependence, the conservation of biodiversity and water, as well as the development of agriculture. For example, F-T jet fuel has been shown to reduce particulate emissions without affecting engine performance. F-T fuel is characterized by excellent thermal stability at elevated temperatures and very good properties at low temperatures.

LIMITATIONS

Potential negative impacts of biofuel usage can be associated with the massive production of a few vegetal species with detrimental effects on global biodiversity and the triggering of market reactions to increased production of feedstock.

Current status and future prospects

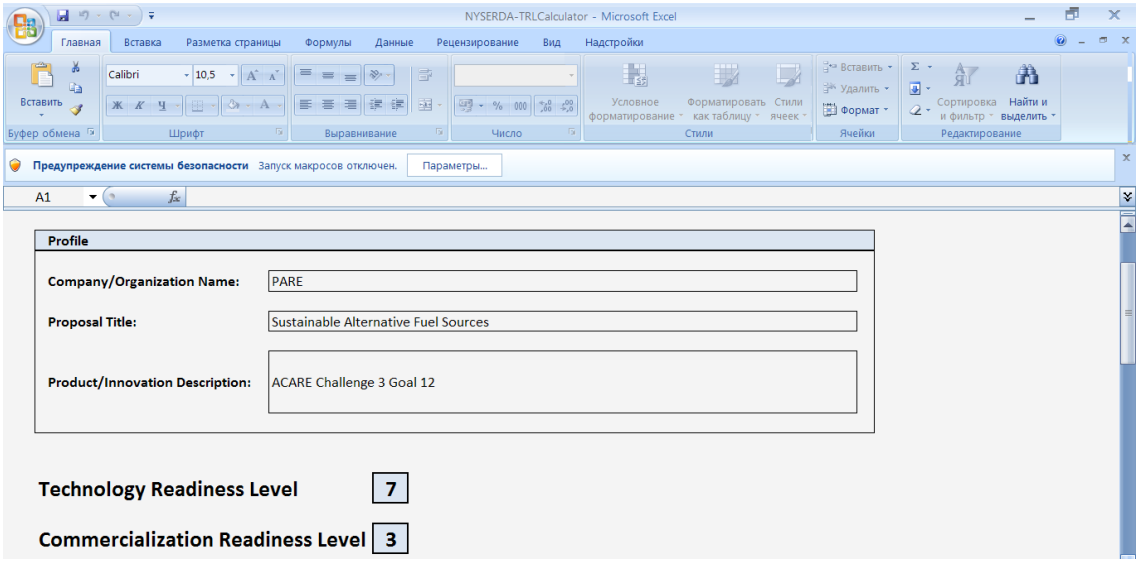
The use of alternative biofuels has been explored under 7thFP European project "ITAKA"[11] (2012-2016). The main milestone achieved concerns the use of bio-jet blend mixed in the conventional airport fuel systems (tanks, pipelines, hydrants) during conventional operation of the airport. This logistics mode appears economically viable, technically feasible and fully compliant with airport operations and users. Since the end of 2015, all flights departing from Oslo airport (Gardermoen) have used a bio-jet fuel blend (below 3%), which corresponds to about 60,000 flights and about 6 million of passengers. The bio-jet fuel was the camelina oil 100% made in the EU. It was produced in Spain (accumulated in three seasons, more than 1000 t), and refined

[11] http://www.itaka-project.eu/nav/pages/progress_results_7.aspx

to bio-jet fuel in Finland. Camelina plantations have been cultivated in a wide range of climatic and soil conditions. As a consequence, camelina yield has varied from 500 to 2,500 kg per hectare, depending on the cultivation and weather/soil conditions. Barley data has been used as an indicator of land quality. So, a farmer harvesting 3,000 kg/ha of barley in a given year should expect a camelina harvest of 1,500 kg/ha (50%). It has been demonstrated that sustainable camelina oil can be produced in Europe, in large amounts, with low risk of ILUC (Indirect Land Use Change), generating additional social and economic benefits for the farmers. The GHG (greenhouse gases) savings in a scaled-up production can achieve a 66% reduction. Besides, the savings can go over 70% if a fertilization strategy is put in place, using i.e. ammonium sulphate (NH_4) instead nitrate (NO_3) for fertilization.

The use of the biofuel has been tested in two series of flights. The first series of 18 long haul flights from Amsterdam to Aruba, on an Airbus A330-200 (carrying around 4,500 passengers informed about the project) was performed using bio-jet fuel blend in one engine to compare the performance of the two engines. No significant performance differences were noted, but that the water accumulated in the tanks during flights can be lowered using the synthetic fuel, reducing the maintenance frequency and costs. The second series of 80 short-haul flights, from Oslo to Amsterdam, on an Embraer E190, carrying about 8,000 passengers, using the camelina bio-jet blend in both engines, confirmed the no detrimental effects on operation with similar or slightly better fuel consumption and, no variation in fuel gauging systems. The flight series was complemented with a series of lab-based emission measurements using a testbed Auxiliary Power Unit (APU). APU emissions tests were completed for the two ITAKA fuel batches and baselined against a standard fossil Jet fuel: performance parameters were as expected quite similar, fuel consumption decrease up to 1% (saving fuel and CO_2 emissions), and the emitted particulate matter (PM) was decreased up to a 50% for a 50:50 fuel blend. PM emissions are a major air quality concern that is linked with a significant number of premature deaths across Europe. High paraffinic fuels such as HEFA bio-jet could significantly help to reduce the impact of this pollutant in the vicinity of airports.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACAREChallenge 3 Goal 12** "Sustainable Alternative Fuel Sources" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.207 grounding on the results of the 1st/2nd year PARE reports (PARE D1.1, 2018, PARE D1.2, 2019).



Category	Answer
Technology	Initial testing of integrated product/system has been completed in a laboratory environment
Product Development	Demonstration of a full scale product/system prototype has been completed in the intended application(s)
Product Definition/Design	The product/system has been scaled from laboratory to pilot scale and issues that may affect achieving full scale have been identified
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Customers/partners have been interviewed to understand their pain points/needs, and business model and value proposition have been refined based on customer/partner feedback
Manufacturing/Supply Chain	Relationships have been established with potential suppliers, partners, service providers, and customers and they have provided input on product and manufacturability requirements

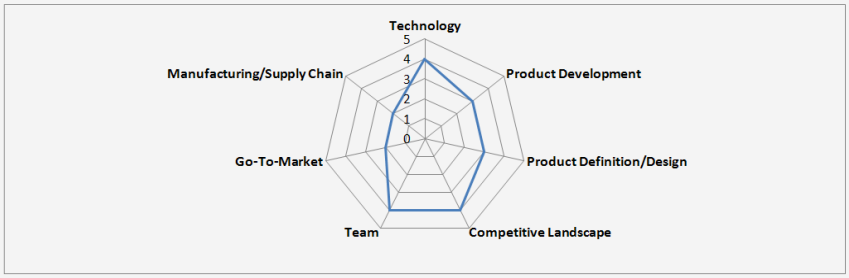


Figure 4.207: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 12 "Sustainable Alternative Fuel Sources"

4.5 Atmospheric Research, Weather and the Environment

** Flightpath 2050 goal 13: "Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritized environmental protection plan and the establishment of global environmental standards".*

Atmospheric hazards have been a safety concern throughout the history of aviation and are addressed in goal 15 (section 4.2), Table 4.45. A better modelling and understanding of atmospheric phenomena can reduce disturbances of air traffic management (goal 5 and section 2.5) and allow an increase of runway capacity at airports (goal 1 and section 2.1). As major users of the airspace aviation can contribute to the monitoring of the atmosphere and to the establishment and implementation of global environmental standards. The monitoring of the atmosphere is performed by a vast array of earth and satellite sensors, plus specialized weather aircraft like those used by NOAA (National Oceanographic and Atmospheric Administration in the US) to fly through tropical storms and collect in-situ atmospheric data. The data transmission capabilities of airliners in modern ATM systems could be used not only for traffic proposes but also to collect atmospheric data in support of environmental standards and policies. It is in the interest of airlines to preserve their flight environment and if appropriate some of the millions of flight around the world could be a source of in-situ measurement and monitoring. More details on the contribution of aviation to the undertakings of atmospheric and weather effects are given in the Key Topic T4.5.

KEY TOPIC T4.5 – WEATHER EFFECT ON AIRCRAFT OPERATIONS

Scope of the goal

Atmospheric research: weather and environment		
Goal 13:Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritized environmental protection plan and the establishment of global environmental standards		
Comparison with2017 SRIA document	Why	Lacks

Coherent	Both the SRIA document and the report mark that the atmospheric hazards will always be a safety concern. Therefore, the monitoring of the atmosphere could be enhanced through specific instruments such as sensors carried on air vehicles as well as information on global atmospheric conditions collected by earth observation and prediction systems.	The SRIA document highlight the climate change effects on aviation, which is not included in the report. According to the document, It will be required to adapt and build resilience to the possible effects of climate change as well as to analyse the new threats that will appear as a consequence of the climate change. It is considered necessary that Europe understands completely the climate change risks in order to be at the forefront of atmospheric research.

Table 4.45: ACARE Flightpath 2050 Goal 13

Benchmarks for Goal 13

There are two ways of assessing the atmosphere impact:

On the one hand, evaluating the impact of the atmosphere on aviation which is analysed in goal 15. In this goal, weather and other hazards from the environment are precisely evaluated and risks properly mitigated.

On the other hand, it is necessary to evaluate the aviation impact on the atmosphere. This impact can be negative such as the CO_2 and NOx emissions and the noise disturbances which are analysed in detail in goal 9.

Finally, within the aviation impact on the atmosphere, it is important to assess how aviation can contribute to the atmosphere knowledge. This is the objective to be evaluated in the goal 13: "Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritized environmental protection plan and the establishment of global environmental standards".

In quantitative terms, the objective to be achieved could be that the 100% of the data that the aircraft can obtain and process from the atmosphere could be shared between other aircraft and ground infrastructure that would allow obtaining a real-time atmospheric model capable of predicting weather hazards as well as to evaluate the possible geographic location of these threats.

In order to achieve this objective, it would be necessary for a series of measures such as those proposed in the following points:

- Aircraft equipped with systems capable of processing a great amount of data
- Communications network
- Real-time broadcast
- Prediction models

AIRCRAFT EQUIPPED WITH SYSTEMS CAPABLE OF PROCESSING GREAT AMOUNT OF DATA

Aircraft would need to have on board systems capable of processing significant amounts of information from the environment (not only atmospheric which is the main purpose of this goal but also another kind of information which can be useful for the rest of goals).

Some initiatives which are currently in development are new modern aircraft engines such as the Pratt & Whitney's Geared Turbo Fan (GTF) engine which is fitted with 5,000 sensors that generate up to 10 GB of

data per second, which could result in 800 TB per day and per engine. Taking into account the goal of 25 million flights, it would be necessary that aircraft generate on average 6000 million TB of data to comply with the goals to be achieved. This is called Aviation 4.0 which is part of the upcoming Industry 4.0 revolution. Industry 4.0 refers to the current trend of higher levels of automation, digitalization and data exchange in manufacturing technologies. It includes cyber-physical systems, the Internet of Things and cloud computing among other technological assets.

Within this Industry 4.0, the concept of aviation 4.0 is introduced, which establish the evolution of commercial aircraft. With this type of digital and smart aeroplane, the amount and diversity of operational data that can be collected on board of the aircraft and by ground operations will raise exponentially. These smart aircraft can sense their environment, self-diagnose their condition and adapt in such a way so as to make the design more useful and efficient thanks to their information technology, measurement science, sensors, actuators, signal processing, cybernetics, artificial intelligence, etc.

In addition, this type of aircraft offers significant improvements in aircraft total weight and manufacturing cost. It also helps to improve the aircraft's life cycle, reduce its maintenance and decrease generated noise. One example of these aircraft is the A350, the new and latest member of the Airbus family.

COMMUNICATIONS NETWORK

An aircraft should have an advanced communication system, capable of transmitting data through multiple datalinks, directly to the ground, to other aircraft and via satellite, digitally and at high speed, providing communication services for all aircraft needs, each with its own required quality of service. In this way, all the detailed information, such as the weather situation, obtained from the on-board equipment and the sensors can be shared between the ground infrastructures and the aircraft in a quickly and reliably. However, this system should be economic so that installing it on as many aircraft as possible will be profitable. In addition, this communication system should be safe, robust and resilient to the possible cyberattacks since the system will need larger bandwidth due to the great amount of data exchanging.

REAL-TIME BROADCAST

The data obtained from the aircraft sensors is broadcasted to all the stakeholders, such as other aircraft and the ground infrastructure in real-time. In this way, the whole system will be aware of the possible weather threats and their possible location. In addition, all this information could be used to develop prediction models that would allow predicting weather hazards in advance.

PREDICTION MODELS

Thanks to all the data obtained from the equipped systems and their broadcasted to other stakeholders, predictions models could be obtained in order to foresee the possible weather hazards.

One example could be to identify and locate the areas with the presence of ice crystals thanks to the sensors equipped in the aircraft. The presence of High-altitude ice crystals causes engine damage and engine power loss. There are some initiatives that research how to identify the formation of these crystals through the sensor TAT (Total Air Temperature). This is because Total Air Temperature (TAT) anomaly has occurred in many cases near the time of the engine power loss events. When this sensor reports zero degrees it is evidence of ice crystals present in the atmosphere. This anomaly is due to ice crystals building up in the area where the thermocouple resides, where they are partly melted by the heater, causing the zero degrees reading. Therefore, TAT anomalies monitoring might alert of areas in which it is probably the presence of High-altitude ice crystals and this information could be shared between other aircraft and the ground infrastructure in real-time. Figure 4.121 illustrates the benchmarks discussed for goal 13.

Reference State in 2010

ENVIRONMENTAL ISSUES AND CLIMATE RISKS

Aviation is one of the most climate/weather sensitive industries. It is affected by changes to visibility, storminess, temperature, icing events, flooding events, and the operational effects of these. Therefore, one of the most important activities is to assess the atmosphere and the environment state in order to predict future climate issues and develop mitigation strategies. This will help to reduce possible disturbances in the airspace and may allow for an increase in airports capacity.

Environmental policy in the European Union developed substantial improvements to the state of the environment. However, there were still major environmental challenges which have significant consequences for Europe, and they continue to be investigated nowadays. Taking this into account, the European environment policy priority areas are the following ones (Figure 4.208):

- Climate change
- Nature and biodiversity
- Natural resources and waste
- Health and quality of life

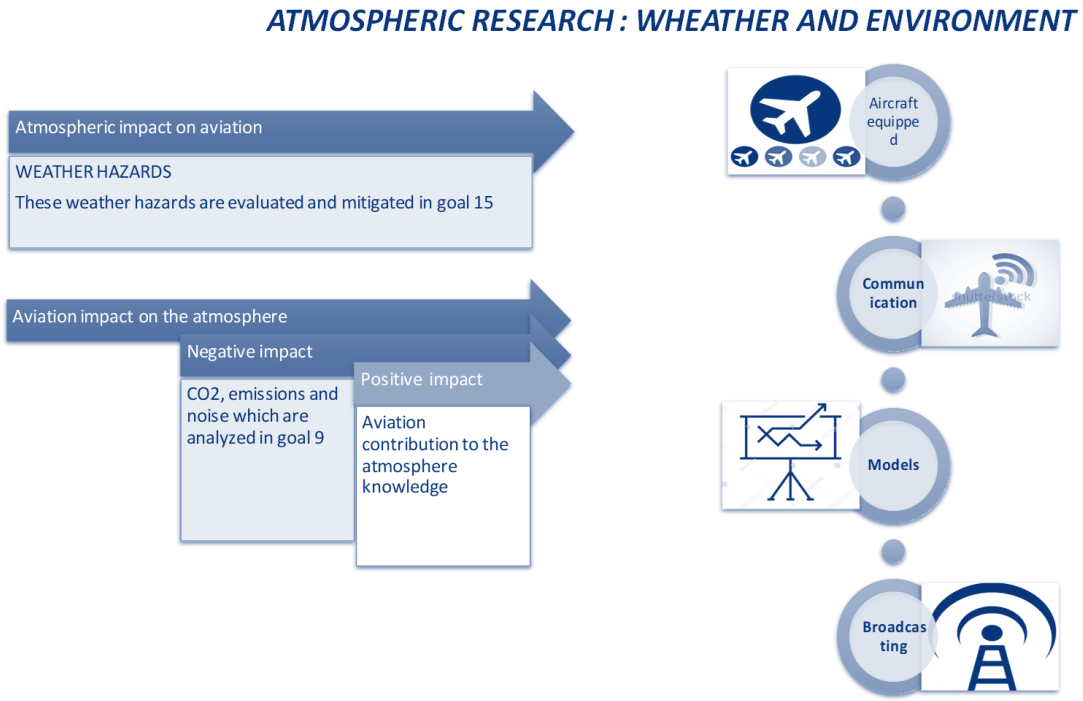


Figure 4.208: Benchmarks for goal 13

➢ Climate change

Climate change has become one of the most environmental concerns since it has a wide range of consequences for biological and socio-economic systems. Aviation is a small but important contributor to climate change and, for that reason, in recent years considerable effort has been carried out to mitigate aviation's impact on the climate and to increase Europe's resilience. Some climate change effects are in the following Table 4.46:

Global mean temperature change	During the 2000-2010 decade there has been a continued increase in the average global temperature with an average of 0,26 C
Greenhouse gas emissions	There has been an increase in carbon dioxide and other trace gases such as methane, ozone and the HCFCs. Aerosols also play a part, by perturbing the Earth's radiative balance
energy efficiency	In the EU, significant improvements in energy efficiency occurred due to technological development in, for example, industrial processes, engines, electrical appliances, etc.
Renewable energy sources	Deployment of renewable energies sources has increased rapidly in recent years, and their share is projected to increase substantially

Table 4.46: Some climate change effects

- Nature and biodiversity

Europe has established an extensive network of protected areas and programmes to reverse the loss of endangered species and the degradation of ecosystems (Table 4.47):

Biodiversity (loss of species)	Climate change is expected to have significant influences on terrestrial biodiversity at all system levels, including species-level reductions in range size and abundance, especially amongst endemic species
degradation of soil	Loss of soil organic carbon results in land degradation, and land degradation is one of the leading challenges for sustainable development and biodiversity conservation

Table 4.47: Endangered species and ecosystem

- Natural resources and waste

Environmental regulation has increased resource efficiency through a relative decoupling of resource use, and waste generation (Table 4.48):

Waste generation	In Europe, resource use and waste generation continue to rise
Waste management	Waste management has been always a focus of EU environmental policies. Such policies, which increasingly require the reduction, reuse and recycling of waste, are contributing to closing the loop of material use

Table 4.48: Waste generation and management

- Environmental and health

Water and air pollution have declined but not enough to achieve good ecological quality in all water bodies or to ensure the good air quality in all urban areas (Table 4.49):

Water quality	The quality of water supply in coastal and island regions is at risk from rising sea level and changes in precipitation. Rising sea level and the occurrence of drought can increase the salinity of both surface water and ground water through saltwater intrusion.
Air quality	the quality of air overpopulated areas is of continuing concern as the degradation of air quality hasa major impact on human health, agricultural productivity and natural ecosystems

Table 4.49: Water and Air quality

All these environmental issues result in climate risks and impacts for aviation which are shown in the following Table 4.50:

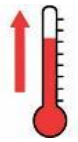
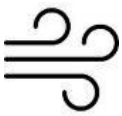
Climate risks	Impact
Precipitation change 	disruption to operations(for example airfield flooding) reduction in airport throughput inadequate drainage system capacity inundation of underground infrastructure (e.g. electrical) inundation of ground transport access (passengers and staff)
Temperature change 	changes in aircraft performance changes in noise impact due to changes in aircraft performance heat damage to airport surface (runway, taxiway) increased heating and cooling requirements
Sea-level rise 	loss of airport capacity impacts on en-route capacity due to lack of ground capacity loss of airport infrastructure loss of ground transport access
Wind changes 	convective weather: disruption to operations and route extensions jet stream: potential increase in en-route turbulence local wind patterns: potential disruption to operations and changes to distribution of noise impact
Extreme events 	disruption to operations, route extensions disruption to ground transport access disruption to supply of utilities

Table 4.50: Climate risks and their impact

MONITORING THE ATMOSPHERE

Taking into account the main environmental issues and their effects on aviation, it is essential to develop a series of methods that allow to assess the atmosphere state and to measure its composition with to face these issues and to develop mitigation strategies.

There are several methods to monitor the atmosphere to state its composition in order to face the global issues mentioned before:

- Routine ground-based measurements
- Systematic aircraft measurements;
- Satellite measurements

➢ Ground-based instrumentation

Thanks to new technologies and a variety of sophisticated measurement techniques, it is possible to measure accurately the atmosphere composition. The globally distributed ground stations provide high-quality observations for:

- detecting long-term trends in atmospheric concentrations;
- monitoring air quality on a regional to global scale;
- evaluating and developing regional to global scale models that include atmospheric chemicals (e.g. local and regional weather and air quality forecast models, long-range transport models and climate models);
- and calibration and validation of satellite observations

Several initiatives monitor and observe the atmosphere such as the Global Atmosphere Watch programme of WMO, which coordinates global ground-based networks measuring greenhouse gases, ozone, UV radiation, aerosols, atmospheric pressure, wind speed and direction, air temperature and relative humidity.

➢ Airborne instrumentation

Thanks to the on-board systems, aviation offers a cost-effective and efficient way of collecting information related to atmospheric conditions and state. Continuous, real-time information captured and communicated by aircraft can be used to update weather observations in a reliably way and to increase weather prediction capabilities. There are several programs whose objective is to evaluate the atmosphere state by using data collected from the aircraft system:

IAGOS (In-service Aircraft for a Global Observing System): it is a European research infrastructure which aims at constructing a global observation system for atmospheric composition by deploying autonomous instruments aboard a fleet of passenger aircraft. It is one component of the European Research Infrastructure for gathering long-term, routine in-situ observational data on the state of the atmosphere. By deploying a set of autonomous instruments aboard passenger aircraft of internationally operating airlines, IAGOS collects crucial atmospheric data at a global scale. The first IAGOS aircraft went into service in 2011, namely aircraft equipped with fully automated instruments for the measurement of several parameters such as ozone, carbon monoxide, and humidity (ICH) and cloud particles (BCP).

MOZAIC (Measurement of Ozone and Water Vapour on Airbus In-service Aircraft): it is a European program that uses automatic instruments for probing atmospheric state parameters and chemical composition, such as water vapour, ozone and carbon monoxide. These instruments have been installed on several commercial aircraft in 1994 and have, since then, provided regular data for the upper troposphere/lower stratosphere with more than 2000 flights and 4000 tropospheric profiles per year.

The SpectraSensors Water Vapour Sensor System (WVSS-II) provides laser fast and accurate measurement of water vapour in the upper atmosphere, which is an essential parameter for accurate weather modelling. The water vapour detection helps to improve the forecasting of weather and climate change. A fleet of aircraft equipped with the Water Vapour Sensor System (WVSS-II) can provide thousands of times the number of vertical profiles accurately, automatically, and at a fraction of the operational cost.

EUFAR: EUFAR was born out of the necessity to create a central network for the airborne research community in Europe with the principal aim of supporting scientists, by granting them access to research aircraft and instruments otherwise not accessible in their home countries. In this way, scientists all over Europe can have an equal chance to carry out various atmospheric and in situ measurements onboard research aircraft.

As can be seen, aircraft measurements are one of the most efficient tools for obtaining representative information of the troposphere and stratosphere at high resolution and with uniform quality.

In addition, these types of measures are really important since global climate change represents one of the most serious environmental issues today. Reliable predictions of the future climate using climate models are central and fundamental requirements for determining future mitigation strategies. The use of commercial aircraft allows the collection of highly relevant observations on a scale and in numbers impossible to achieve using research aircraft, and where other measurement methods (e.g., satellites) have technical limitations.

Land and sea bared sensors and data collected by aircraft are complemented by satellites.

- Satellite instrumentation

Compared to measurements made by ground-based sensors (land-based and buoys) and by airborne instrumentation (aircraft and balloons), the advantage of space-borne sensors is their global three-dimensional coverage and regular repeat cycle.

Meteorological satellites have been successfully used for tropospheric measurements of clouds and other parameters required for weather prediction. Geostationary satellites can be used to measure wind velocity by tracking clouds and water vapour. Satellite sensors, communications and data assimilation techniques are evolving steadily so that better use is being made of the vast amount of satellite data. Improvements in numerical modelling, in particular, have made it possible to develop increasingly sophisticated methods of deriving the temperature and humidity information directly from the satellite radiances.

Research satellites, such as ENVISAT and AURA, contribute strongly to monitor atmosphere composition.

ENVISAT: Envisat was launched as an Earth observation satellite. Its objective was to service the continuity of European Remote-Sensing Satellite missions, providing additional observational parameters to improve environmental studies. Currently, scientific disciplines use the data acquired from the different sensors on the satellite, to study such things as atmospheric chemistry, ozone depletion, biological oceanography, ocean temperature and colour, wind waves, hydrology (humidity, floods), agriculture and arboriculture, natural hazards, digital elevation modelling (using interferometry), monitoring of maritime traffic, atmospheric dispersion modelling (pollution), cartography and study of snow and ice. The contact with the satellite was lost in 2012.

AURA. Aura is a multi-national NASA scientific research satellite in orbit around the Earth, studying the Earth's ozone layer, air quality and climate. The scientific findings of these studies address key NASA research objectives related to stratospheric composition, air quality, and climate change.

Aura's instruments measure trace gases in the atmosphere by detecting their unique spectral signatures. MLS (Microwave Limb Sounder) observes the faint microwave emissions from rotating and vibrating

molecules. HIRDLS (High-Resolution Dynamics Limb Sounder) and TES (Tropospheric Emission Spectrometer) observe the infrared thermal emissions also due to molecular vibrations and rotations. OMI (Ozone Monitoring Instrument) detects the molecular absorption of backscattered sunlight in the visible and ultraviolet wavelengths.

Progress up-to-now

A brief description of current European projects is shown below.The objective of these projects is to assess the atmosphere state through ground and satellite infrastructure:

Copernicus: previously known as the Global Monitoring for Environment and Security (GMES) programme, Copernicus is a European Union programme aimed at developing European information services based on satellite Earth Observation and in situ (non-space) data. The provision of Copernicus services is based on the processing of environmental data collected from Earth observation satellites and in situ sensors.Copernicus services are based on information from a dedicated constellation of satellites, known as "Sentinels", as well as tens of third-party satellites known as "contributing space missions", complemented by "in situ" (meaning local or on-site) measurement data. In situ data are an essential and integrated part of Copernicus used to provide robust integrated information and to calibrate and validate the data from satellites (e.g. ground-based weather stations, ocean buoys and air quality monitoring networks).

EUMESAT: is the European operational satellite agency for monitoring weather, climate and the environment. EUMETSAT operates a fleet of satellites in geostationary and polar orbit, which provide a wide array of Earth observation data for weather, climate and environmental monitoring. The ground segment constitutes the ground-based infrastructure necessary to support the operation of the satellites, including the control of the spacecraft in orbit, and the acquisition, reception, processing and delivery of their data.

The Global Atmosphere Watch (GAW): it is a programme of WMO which provides reliable scientific data and information on the chemical composition of the atmosphere, its natural and anthropogenic change, and helps to improve the understanding of interactions between the atmosphere, the oceans and the biosphere. Monitoring has focused on greenhouse gases and aerosols for possible climate change, ozone and ultraviolet radiation for both climate and biological concerns, and certain reactive gases and the chemistry of precipitation for a multitude of roles in pollution chemistry.

Finally, it is important to note that, in this objective, it is very difficult to differentiate between the 2010 state of the art and the 2017 state of the art due to several reasons:

On the one hand, the European projects mentioned before, which have as objective monitoring the atmosphere, has been in development for several years. On the other hand, the main environmental issues described before (such as climate change), that concern nowadays and which arose years ago, are still under study.In addition, it is important to highlight that the timeframe of these aspects extends into a broader period. For these reasons, it is difficult to evaluate accurately the progress made from 2010 to 2017.

Existing technologies, breakthrough technologies and evolutionary progress up-to-2050

Atmospheric composition matters to several areas such as climate, weather forecasting, human health, terrestrial and aquatic ecosystems, aeronautical operations, etc. Due to its importance, it is necessary to develop new and enhanced methods to evaluate its composition in order to better understand the future environmental issues and carry out mitigation plans. The principal missions and goals for long-term horizon are the following ones:

- Ensuring that the climate continues to be monitoring by applying new techniques that provide better predictions.

- Improving global, regional and local long-term climate forecasts
- Observing atmospheric additional parameters
- Many environmental issues that should be considered in the future, which are explained in the section.

ENVIRONMENTAL ISSUES AND CLIMATE RISKS

As it happened nowadays, climate change will be considered as the main environmental issue of risk. Although in recent years the aviation sector has initiated several measures and actions to mitigate the climate change effects, it is clear that its effects will not be fully neutralized and, as a consequence, some degree of climate change will be inevitable. In addition, other environmental hazards will emerge and, therefore, new mitigations strategies will be necessary. Moreover, taking this into account the aviation sector will need to build climate resilience and to adapt to the emerging threats.

In the following Table 4.51, it is shown the main climate risks, their effects and their impact on European aviation. It covered a time horizon up until 2050, a period where initial impacts may begin to be experienced by the industry.

Changes to temperature, precipitation, and storm patterns are all expected in the near-term, certainly by 2030. The impacts of sea-level rise are more gradual and not expected until later in the century. However, more frequent and intense storm surges will have an earlier impact, reducing capacity and increasing the delay.

ENVIRONMENTAL ISSUES FORECASTS BY REGION

In the following images, it can be seen the potential environmental issues and their main impacts on aviation in Europe. It is expected that these possible effects vary greatly with the region as shown in Figures 4.209 and 4.210:

Environmental issues	Primary effects	Possible aviation impacts
Temperature change	❑ Higher mean temperatures, especially in winter for Northen Europe and summer for South Europe. ❑ Higher, colder tropopause	❑ Runway demand mismatch ❑ Airspace demand mismatch ❑ Cruise altitude changes ❑ Airspace design changes ❑ Aircraft performance changes
Snow and frozen ground	❑ Fewer days of snow/frost	❑ Demand re-distribution ❑ Changed de-icing and snow clearance requirements
Precipitation and water supply	❑ Increased precipitation in Northen Europe ❑ Increased freezing rain ❑ Decreased precipitation in South Europe	❑ Airport and runway demand mismatch ❑ Loss of Airport availability and hence perturbation and delay ❑ Reduced ability to meet demand due water shortages
Sea level	❑ Higher mean sea level ❑ Increased impacts of storm surges and flooding	❑ Loss of Airport availability ❑ Loss of ground access to airports ❑ Delay and perturbation ❑ New airports or infrastructure required
Convective weather	❑ Increased intensity of precipitation events, lightning, hail and thunderstorms	❑ Disruption and delay ❑ Potential safety issues if frequency and severity increases Potential loss of en-route capacity
Visibility	❑ Decrease in winter days affected by fog	❑ Fewer capacity restrictions due to reduced visibility ❑ Reduced business case for lo-visibility related technologies

Table 4.51: Environmental issues and their implications for aviation

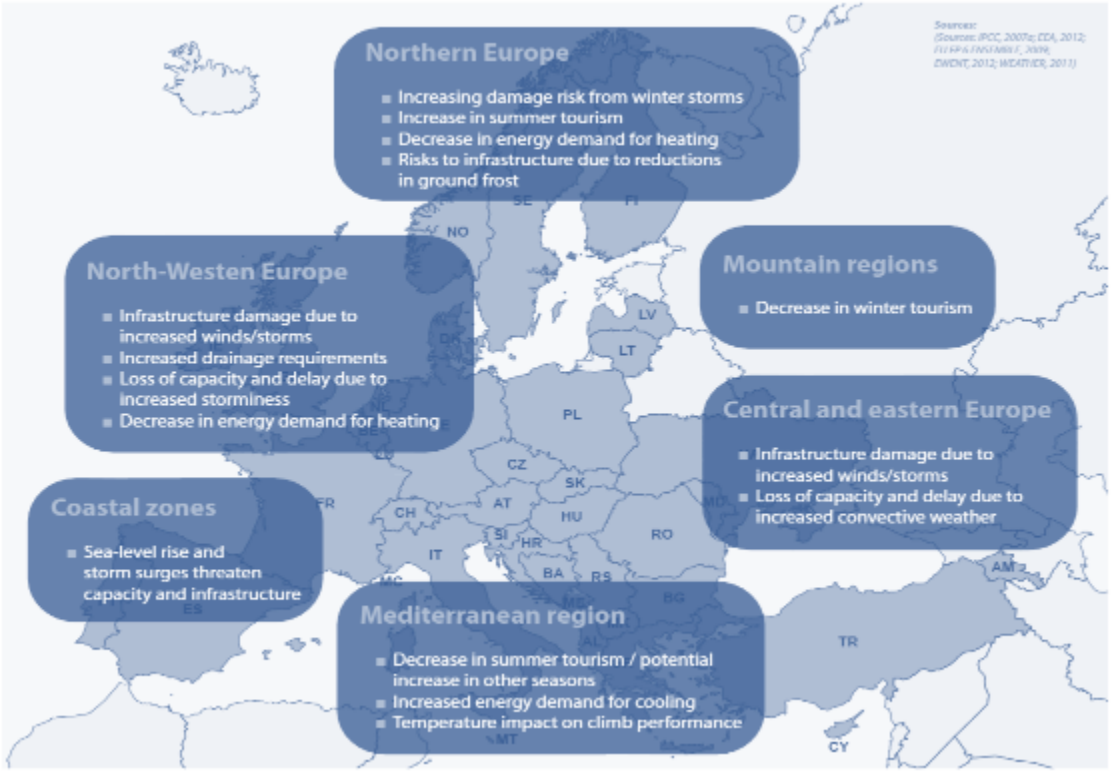


Figure 4.209: Environmental issues effects by region

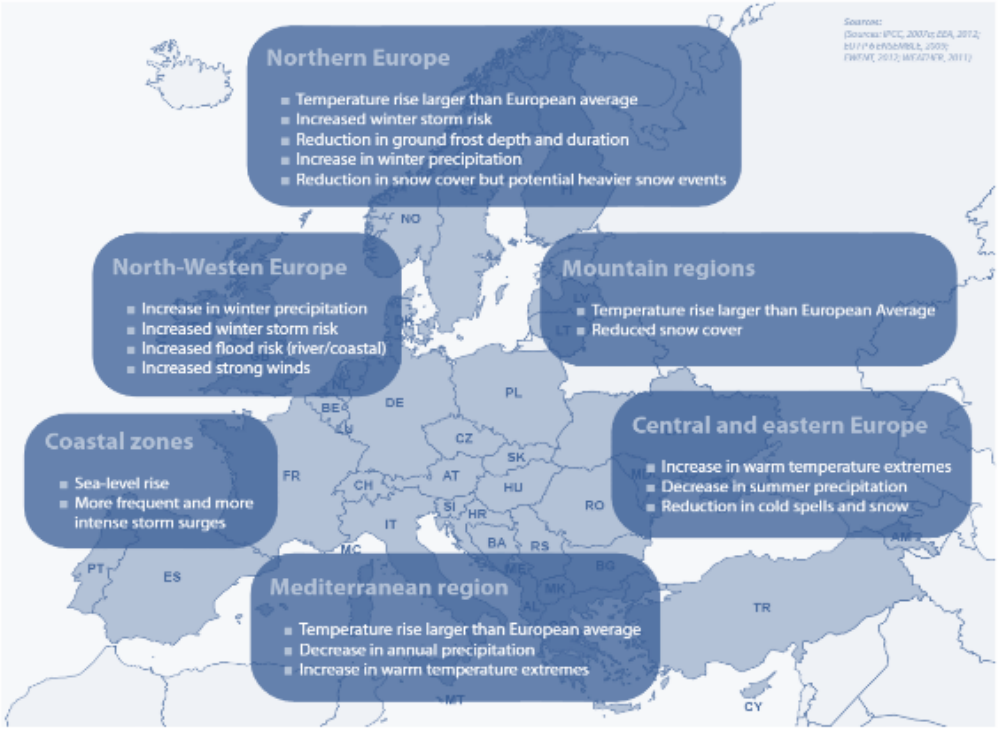


Figure 4.210: Environmental issues impacts on aviation by region

DURATION AND TIMING OF ENVIRONMENTAL IMPACTS

In this section, it is analysed the timeline of the main future environmental issues and how they will affect the aviation industry. It is expected that environmental issues will predominantly affect infrastructure and operations (Table 4.52). However, some impacts may not be a concern until the middle of the century while others may be experienced sooner.

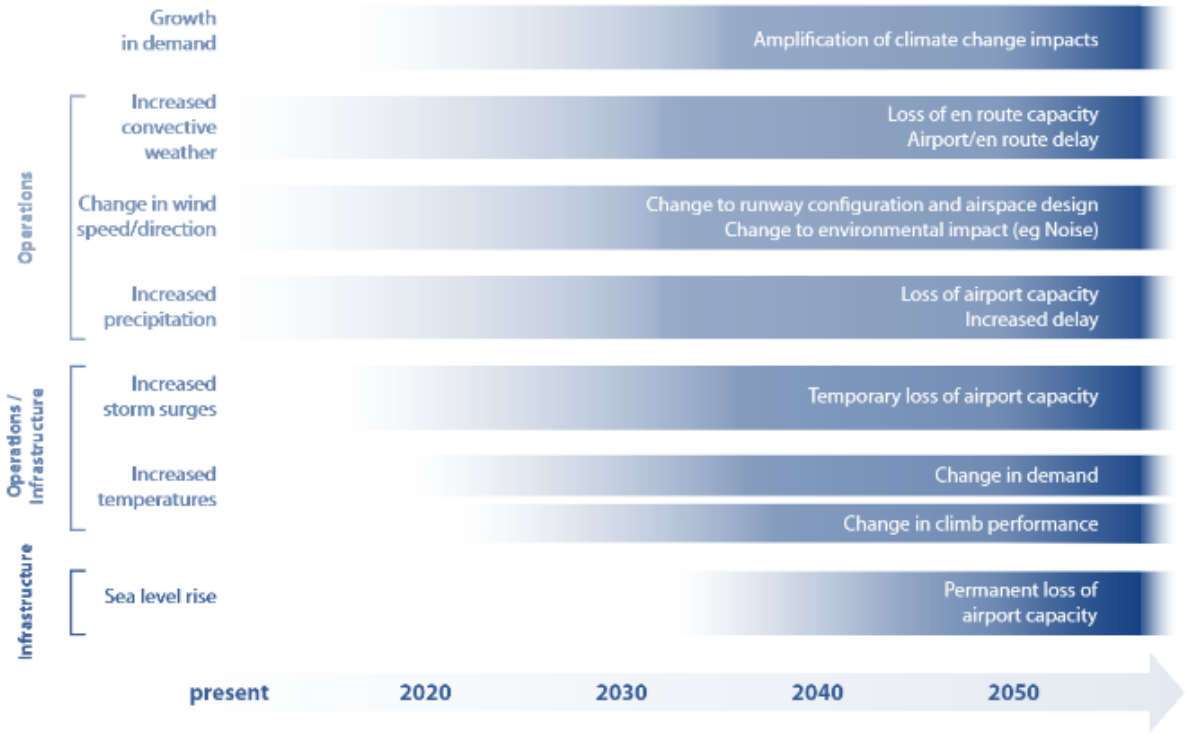


Table 4.52: Effects of climate change on aviation

ATMOSPHERE COMPOSITION

To face the environmental issues mentioned previously, it is essential to have a better knowledge of the atmospheric composition in order to achieve better forecasts and predictions that would allow developing mitigation strategies. There are several initiatives and projects which are currently in development and they are expected to progress significantly in the long term. Their main methods to monitor atmosphere are based on satellite and airborne instrumentation. Some examples of these projects are described in the following sections.

SATELLITE INSTRUMENTATION:

- Copernicus project:

Copernicus is the European system for monitoring the Earth and it is coordinated and managed by the European Commission. It consists of a complex set of systems which collect data from multiple sources: earth observation satellites and in situ sensors such as ground stations and airborne sensors. It processes this data and provides users with reliable and up-to-date information through a set of services related to environmental and security issues. Copernicus: The Copernicus programme is supported by a dedicated constellation of satellites, known as "Sentinels", which are specifically designed to meet the needs of the Copernicus services and their users. The first of these sentinels was launched in 2014 and it is expected to launch more satellites in the next years. Copernicus also draws on a large number of in situ (meaning on-site or local) measurement systems put at the disposal of the programme by the EU Member States. These include sensors placed on the banks of rivers, carried through the air by weather balloons, pulled through the sea by ships, or floating in the ocean. In situ data are used to calibrate, verify and supplement the information provided by satellites, which is essential to deliver reliable and consistent data over time.

Copernicus improves the capabilities to monitor, forecast and make projections about the changing climate, by increasing the number and sources of raw data at disposal, producing services based on integration, modelling and analysis of these data, and by coordinating the production of certified climate information from multiple sources. With the new satellites that are expected to be launched in the next years, these measurements, predictions and projections of the climate will be more accurate and reliable. The sentinels programme launch is presented below in the Figure 4.211.

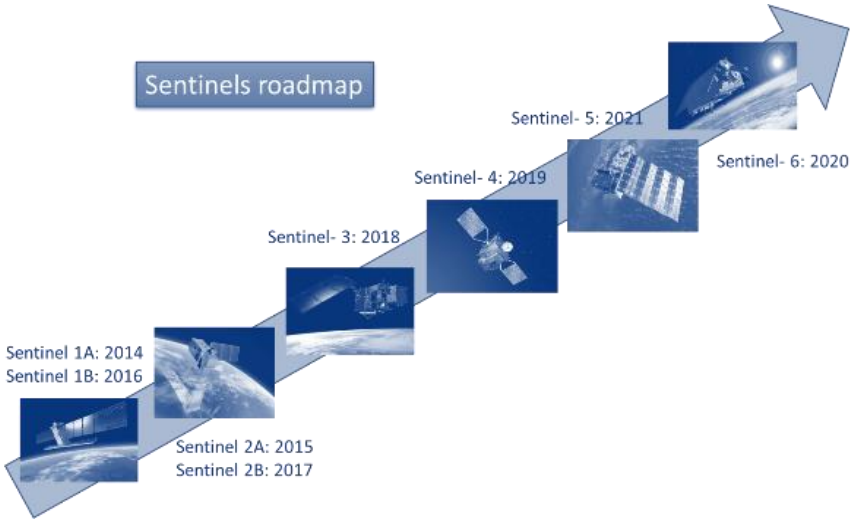


Figure 4.211: The Sentinel families of European environmental satellites

The Sentinel-1 mission is designed as a two polar-orbiting satellites constellation: Sentinel-1A, the first satellite that was launched on 3 April 2014 and Sentinel-1B which was launched on April 2016. Sentinel-1 is a radar imaging satellite which delivers images day and night under all weather conditions, for land and sea monitoring.

Sentinel-2 provides high-resolution optical imagery for land services. It provides, for example, the imagery of vegetation, soil and water cover, inland waterways and coastal areas. Sentinel-2 also delivers information for emergency services. The twin satellites Sentinel-2A and Sentinel-2B were respectively launched on June 2015 and on March 2017.

Sentinel-3 will provide high-accuracy optical, radar and altimetry data for marine and land services. It measures variables such as sea-surface topography, sea- and land-surface temperature, ocean-colour and land colour with high-end accuracy and reliability. The first Sentinel-3 satellite (S-3A) was launched in February 2016 and is supporting ocean forecasting systems, as well as environmental, agriculture and climate monitoring. A second satellite (S-3B) is scheduled for launch in 2018.

Sentinel-4 will provide data for atmospheric composition monitoring. Its objective is to monitor key air quality trace gases and aerosols over Europe at high spatial resolution with a fast (hourly) revisit time. It will be a payload embarked on EUMETSAT's Meteosat Third Generation (MTG), which is scheduled to be launched around 2019.

Sentinel-5 will also be dedicated to atmospheric composition monitoring. It will be a payload embarked on a EUMETSAT's Metop Second Generation (Metop-SG) to be launched in 2021 timeframe. It will provide accurate measurements of key atmospheric constituents such as ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide, methane, formaldehyde, and aerosol properties.

Sentinel-6 will provide high accuracy altimetry for measuring global sea-surface height, primarily for operational oceanography and for climate studies. It is a cooperative mission developed in partnership

between Europe (EU, ESA and EUMETSAT) and the U.S. (NOAA and NASA). It is planned for launch in 2020, as shown in the Sentinel maturity plan (Figure 4.212).

As it can be, the launch of new satellites will provide better predictions and measurements of the atmosphere thanks to new advanced instruments and techniques.

Sentinels projection

- COSMIC mission

New research indicates that the COSMIC microsatellite system (Figure 4.213), which uses a technology known as GPS radio occultation to observe remote regions of the atmosphere, can significantly improve predictions of climate.

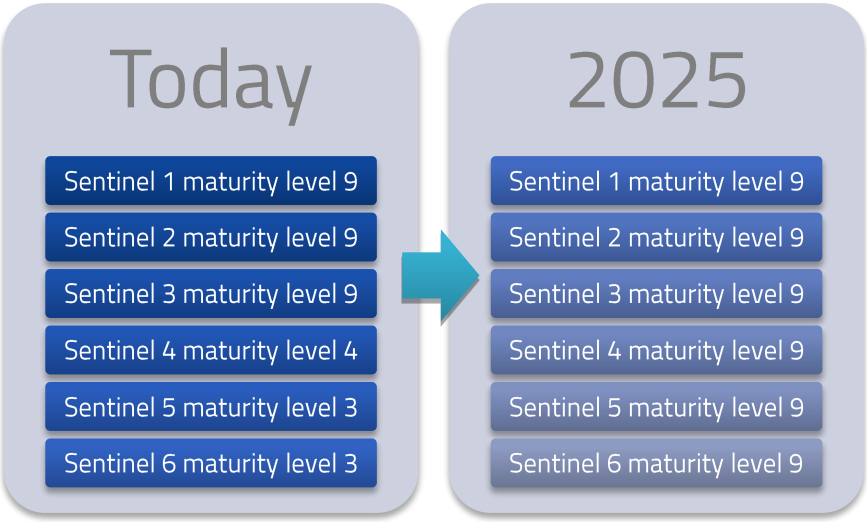


Figure 4.212: Maturity Plan for the Sentinel family

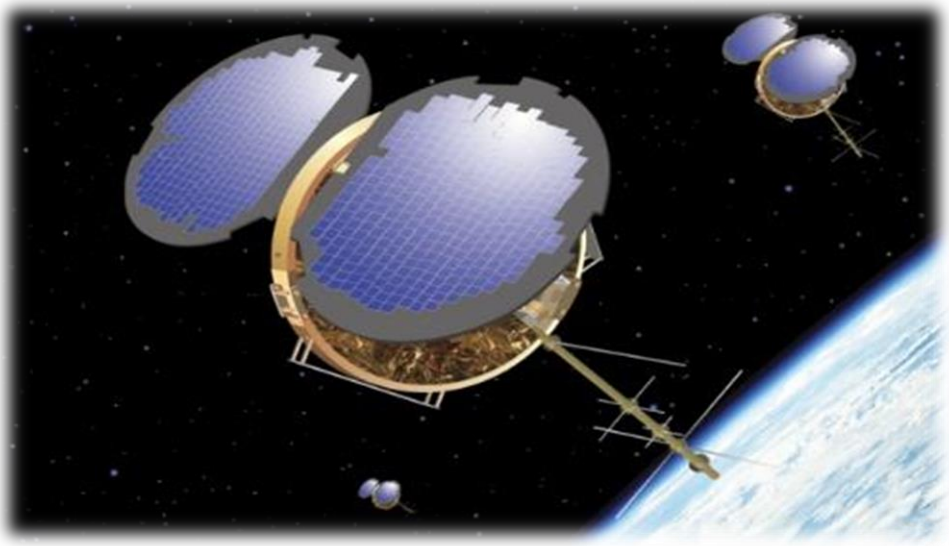


Figure 4.213: Cosmic microsatellite system

The COSMIC mission (Constellation Observing System for Meteorology, Ionosphere, and Climate) is a collaborative project between Taiwan and the United States to demonstrate the use of the radio occultation

(RO) technique for weather prediction, climate monitoring, and space weather forecasting. The two countries plan to launch an additional six COSMIC satellites in 2016 and another six in 2018, which will give forecasters and researchers far more data.

Forecasts traditionally draw on observations taken by instruments on Earth's surface or by radiosondes, which are lifted into the atmosphere by balloons. But both these approaches are limited in hard-to-access places, like the open ocean. In contrast, GPS radio occultation measurements can be made almost anywhere, and they are unaffected by clouds, light rain, or airborne aerosols. By using GPS signals to monitor the atmosphere in three dimensions, the FORMOSAT-3/COSMIC satellite constellation has led to improved global weather monitoring, especially in data-sparse regions. This microsatellite system has proved its value, providing many applications for weather forecasting.

Applications:

Weather

- Improve global weather analyses, particularly over data-void areas (such as oceans and polar regions)
- Improve the skills of global and regional weather prediction models
- Improve understanding of tropical, midlatitude, and polar weather systems and their interactions

Ionosphere and space weather

- Observe global electron density distribution
- Improve the analysis and prediction of space weather
- Improve monitoring/prediction of scintillation and related phenomena (e.g., equatorial plasma bubbles, sporadic E clouds)

Climate

- Monitor climate change and variability with unprecedented accuracy and precision.
- Evaluate global climate models and analyses
- Calibrate infrared and microwave sensors

Data collected by COSMIC are especially useful for forecasting tropical cyclones, including typhoons and hurricanes. In addition, COSMIC is able to provide critical observations of water vapour, the fuel that drives tropical cyclones, in high vertical resolution, which means that scientists can determine how much water is present at what height in the atmosphere.

➢ Advanced Satellite Aviation Weather Products (ASAP)

The Advanced Satellite Aviation weather Products (ASAP) initiative has been developed to provide satellite-derived meteorological products and expertise to the Federal Aviation Administration (FAA) weather research community. Research areas important to the aviation community that are addressed by the ASAP initiative include:

1. **Convective Weather (Figure 4.214)**

- Develop satellite-based information that will aid in the real-time now casting of convective initiation (CI) and the diagnosis of convection on meso-and synoptic scales.
- Develop a series of CI "interest fields" from existing satellite sensors that can help predict future convection on local scales (i.e., 1-4 km).
- Develop new methods for using hyperspectral data for accomplishing these goals.

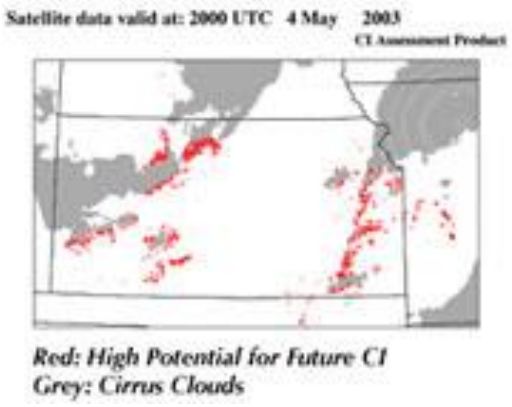


Figure 4.214: Convective initiation

2. Turbulence Detection (Figure 4.215)

Develop satellite-based techniques to identify and characterize regions of moderate and severe clear-air (e.g., mountain waves), and cloud-induced turbulence (e.g., thunderstorms), as detectible in GOES, and especially MODIS infrared data.
Develop value-added products of turbulence from satellite data sets that can be used in conjunction with numerical simulation and existing PDT turbulence prediction systems.

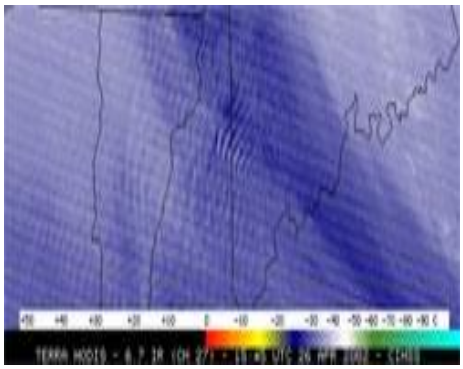


Figure 4.215: Turbulence Detection

3. Oceanic Weather (Figure 4.216)

Apply satellite-based information that will aid in the forecasting and analysis of hazardous weather over oceans. Overlaps with other PDT efforts.
Use products that help identify regions of high flight-level winds, dust, turbulence, convection, and clouds that can assist in trans-oceanic travel.

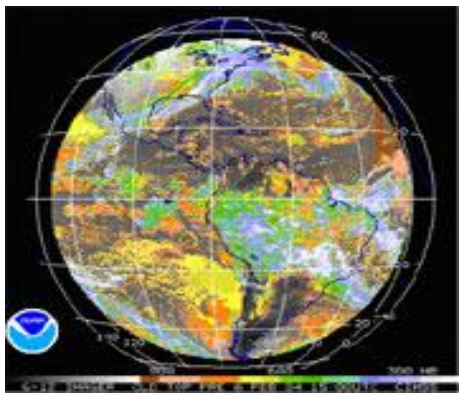


Figure 4.216: Oceanic Weather

4. Cloud Properties (Figure 4.217)

Develop satellite-based information that will aid in the real-time diagnosis of cloud microphysical properties and cloud type.
Emphasize use of MODIS imagery and other high-spectral resolution data.

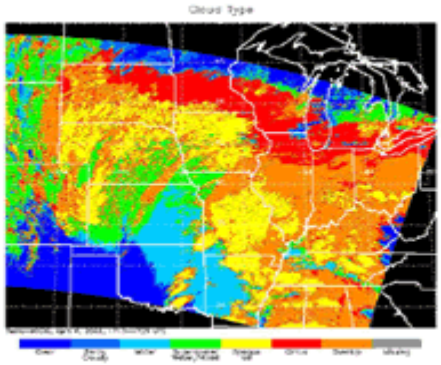


Figure 4.217: Cloud properties

5. Volcanic Ash (Figure 4.218)

Develop satellite-based information that will aid in the real-time diagnosis of volcanic ash, ash clouds and ash characteristics.
Emphasize the use of MODIS imagery and other high-spectral resolution data.

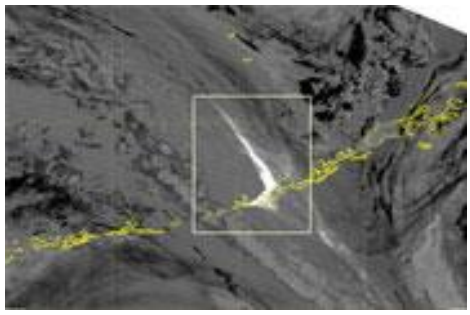


Figure 4.218: Volcanic Ash

6. Winds (Figure 4.219)

Incorporate satellite-derived winds to identify possible turbulent regions associated with upper tropospheric jets.

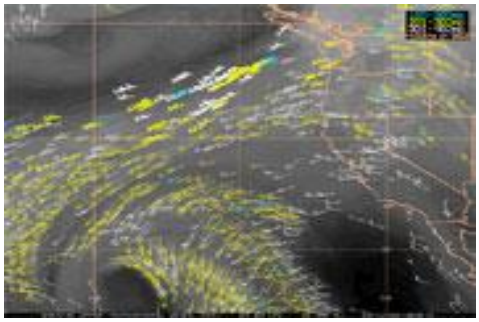


Figure 4.219: Winds

➢ EUMETSAT

EUMETSAT is the European operational satellite agency for monitoring weather, climate and the environment. It operates a system of meteorological satellites that observe the atmosphere and ocean and land surfaces – 24 hours a day, 365 days a year. This data is supplied to the National Meteorological Services of the organisation's Member and the Cooperating States in Europe, as well as other users worldwide. Its main objectives include identifying and monitoring the development of potentially dangerous weather situations as well as issuing timely forecasts and warnings to emergency services and local authorities, helping to mitigate the effects of severe weather. EUMETSAT operates a fleet of satellites in geostationary and polar orbit, being the Meteosat Second Generation (MSG) the satellites which are currently operative, providing images of the whole Earth, and data for weather forecasts. Some applications of these satellites are monitoring convective storms, volcanic ash clouds and the distribution and behaviour of fog.

EUMETSAT is planning and developing (Figure 4.220) the future satellite systems required to deliver and further improve observational inputs to forecasting and climate monitoring in the 2020-2040 timeframe. This is carried out in cooperation with the European Space Agency (ESA). The projects which are being prepared for the long-term future are Meteosat Third Generation (MTG) and EUMETSAT Polar System Second Generation (EPS-SG).

The Meteosat Third Generation (MTG) programme was fully approved by the EUMETSAT Member States in February 2011, thereby establishing the first pillar of EUMETSAT's future in the 2020-2040 timeframe. The MTG programme will revolutionise weather forecasting and environmental monitoring by providing a significant improvement over the capabilities of the current Meteosat generation. It should guarantee access to space-acquired meteorological data until at least the late 2030s. The Satellite Concept is based on:

- Four Imaging Satellites (MTG-I) (20 years of operational services expected)
- Two Sounding Satellites (MTG-S) (15.5 years of operational services expected)

Therefore, the satellite series will comprise four imaging and two sounding satellites. The imaging satellites, MTG-I, will fly the Flexible Combined Imager (FCI) and the Lightning Imager (LI), an imaging lightning detection instrument. The sounding satellites, MTG-S, will include an interferometer, the Infra-red Sounder (IRS), with hyper-spectral resolution in the thermal spectral domain, and the Sentinel-4 instrument, the high-resolution Ultraviolet Visible Near-infrared (UVN) spectrometer. Such improvements will allow better are spatial resolution and as a consequence, better predictions and forecasts.

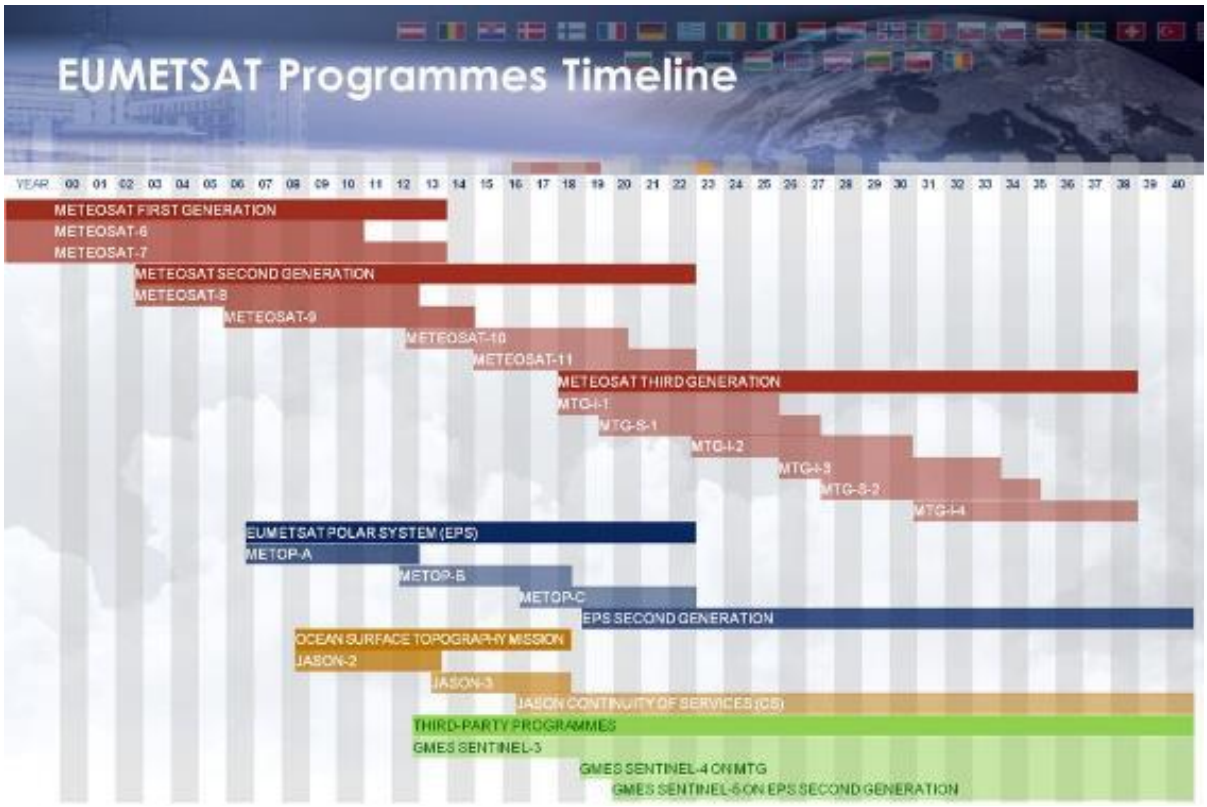


Figure 4.220: Successive generation of EUMETSAT

- The EUMETSAT Polar System Second Generation (EPS-SG) is the second pillar (Figure 4.221, 4.222) of EUMETSAT's future, expected to continue the global observations of EPS in the 2020-2040 timeframe.

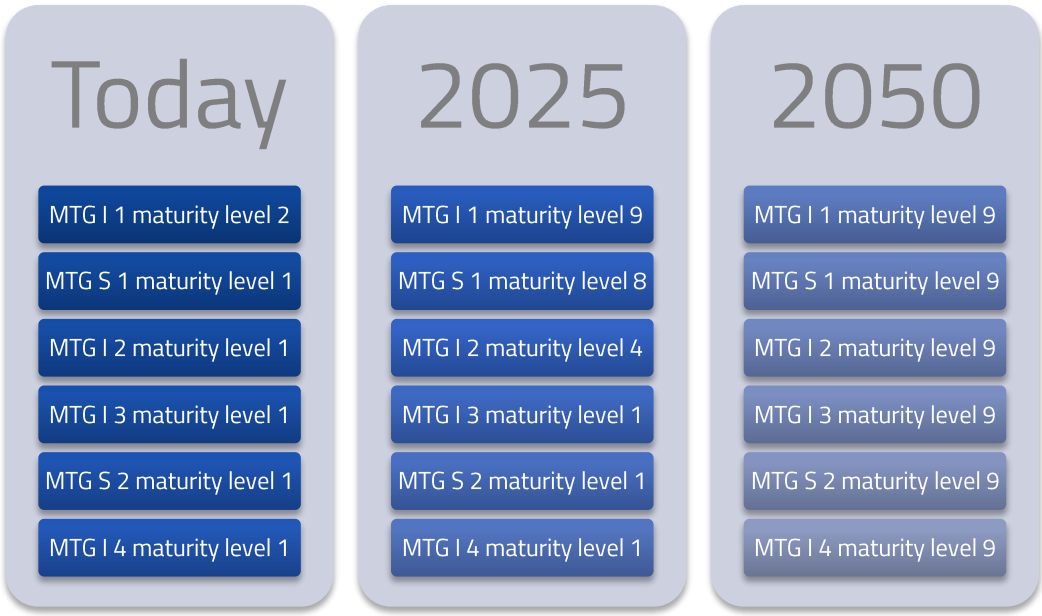


Figure 4.221: Meteosat Third Generation Satellite Maturity Plan

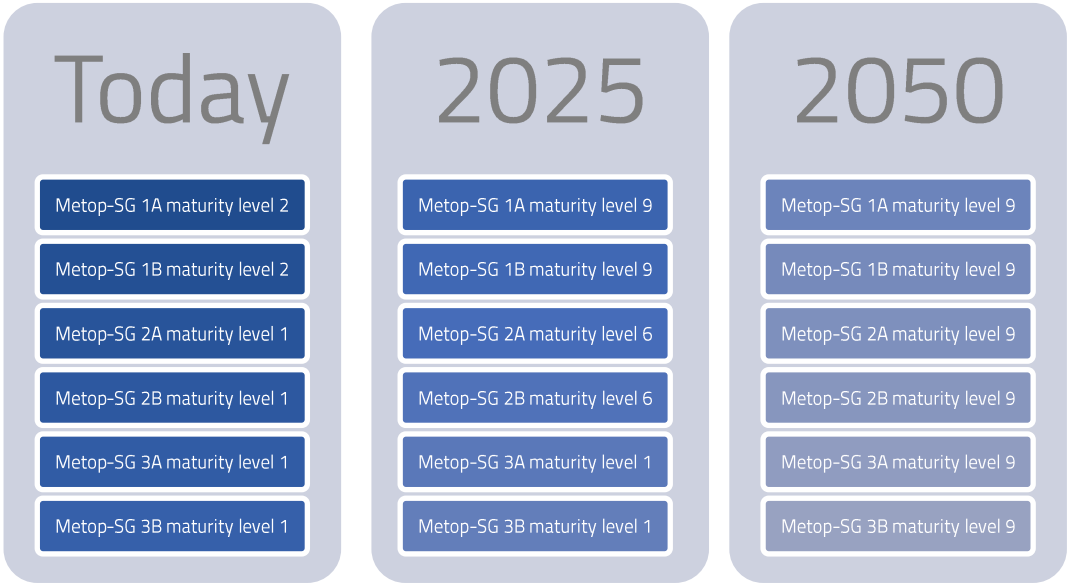


Figure 4.222: Polar System Second Generation (EPS-SG) Projection

- The main priorities of the programme will be to support operational weather forecasting and to provide operational services in support of climate monitoring and new environmental services. EPS-SG represents Europe's contribution to the future Joint Polar System (JPS), which is planned to be established together with the National Oceanic and Atmospheric Administration (NOAA) of the United States, following on from the Initial Joint Polar System (IJPS). Polar-orbiting satellites, due to their global coverage and of the variety of passive and active sensors that can be deployed from Low Earth Orbits, have the most significant positive impact on Numerical Weather Prediction (NWP). The EPS-SG system will provide global, regional and local data service. The EPS-SG Programme is expected to be one of the most important sources of satellite observations for all forecasts based on NWP in the 2021–2040 time frame. In the next image it can be seen the overview of EUMETSAT programs, with all the satellites programme launches:

Meteosat Third Generation Projection:

In the next image (Figure 4.223), it can be seen the data that will be provided by monitoring satellites mentioned before.

AIRBORNE INSTRUMENTATION

The main current project which provides atmospheric data through airborne instrumentation is the IAGOS project. In-service Aircraft for a Global Observing System (IAGOS) is a European Research Infrastructure for global observations of atmospheric composition from commercial aircraft. IAGOS combines the expertise of scientific institutions with the infrastructure of civil aviation in order to provide essential data on climate change and air quality at a global scale. In order to provide optimal information, two complementary systems have been implemented:

- IAGOS-CORE providing global coverage on a day-to-day basis of key observables. IAGOS-CORE cooperates with several airlines for quasi-continuous measurements of trace gases, aerosol and cloud particles from a fleet of long-haul passenger aircraft. Each aircraft is equipped with the IAGOS-CORE rack which contains all necessary provisions for installing fully automated instruments for the measurement of ozone, carbon monoxide, humidity and cloud particles.
- IAGOS-CARIBIC providing a more in-depth and complex set of observations with lesser geographical and temporal coverage. IAGOS CARIBIC is an innovative scientific project to study and monitor important chemical and physical processes in the Earth's atmosphere. Detailed and extensive measurements are made during long-distance flights. CARIBIC deploys a modified airfreight container with automated scientific apparatus which are connected to an air and particle (aerosol) inlet underneath the aircraft.



Figure 4.223: Image obtained by several environmental satellite system

In the following images (Figure 4.224), it can be seen examples of installation of IAGOS-CORE instrumentation aboard aircraft. At present time, eight aircraft are flying for IAGOS (one with IAGOS-CARIBIC and seven with IAGOS-CORE).

Therefore, the technology for monitoring atmosphere through the onboard system already exists and the objective is to expand this technology. That is to say, the purpose of the future will be to increase the fleet of aircraft with this technology on-board. The long-term plan is to increase the number of aircraft to 20 in order to further enhance the geographical coverage. New instruments will be developed in response to future scientific and societal challenges.



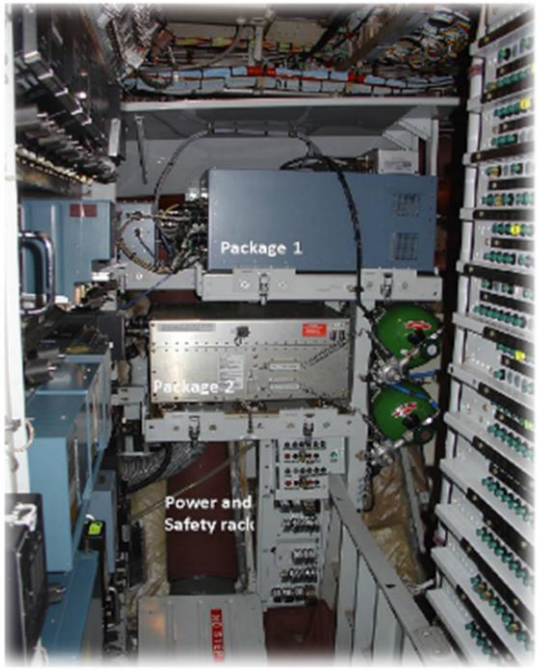


Figure 4.224: Instrumentation installed in aircraft for environmental purpose

Timeline Projection:

As technology has already been deployed, the corresponding TRL is number 9. Therefore, the projection which is represented below is the expansion of this technology. Taking into account that the current IAGOS fleet is 8 aircraft the projection could be as shown in Figure 4.225.

The IAGOS project is only one of several projects which use aircraft onboard systems to measure the atmospheric composition. In the future, the objective will be to **equipped aircraft** in a massive way with this type of instruments. In this way, the atmospheric composition measurement will be more accurate and reliability. In addition, one initiative of recent years is to use **drones** to measure atmospheric composition since a drone will be able to fly to any point in the vertical atmosphere and take air sample readings and transmitting them to a ground computer for monitoring. They could also be used on routes which aircraft normally do not use and provide atmosphere data closer to the ground. These two measures will suppose the main breakthrough in the future.

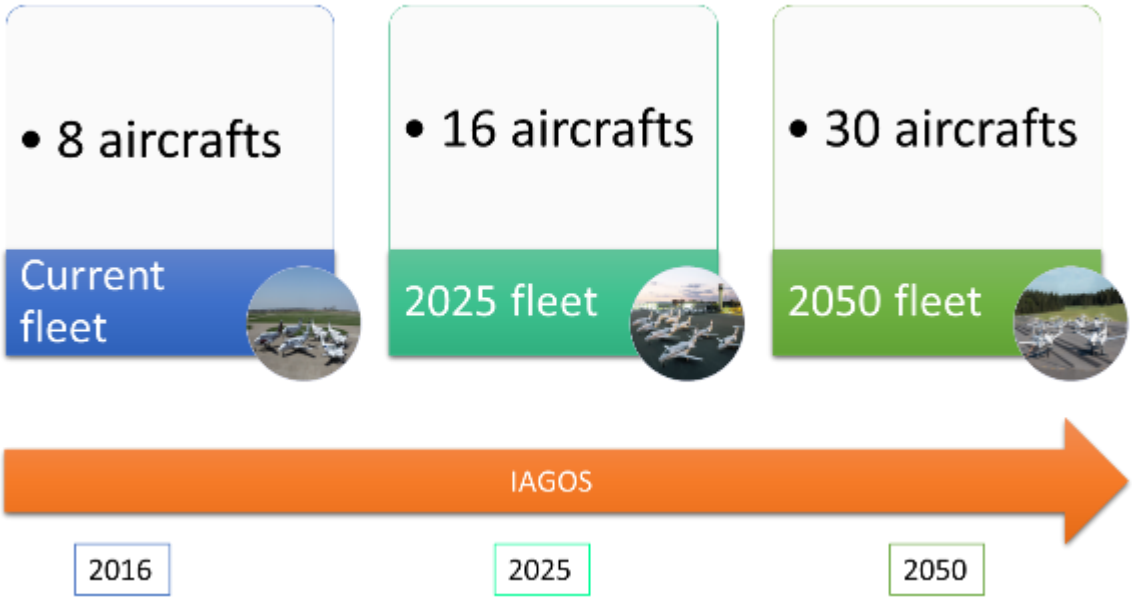


Figure 4.225: Expected growth in the size of the fleet of aircraft equipped with IAGOS instrumentation

BREAKTHROUGH MEASURES TO MONITOR ATMOSPHERE

In the future, three possible ways of development that could suppose breakthrough:

- Equipped aircraft in a massive way with instruments capable of measuring atmospheric parameters;
- Using drones to monitor the atmosphere;
- Alternative ways to measure atmospheric parameters (the weather company);

In the following sections are described the previous measures that could suppose breakthroughs in the way in which the atmosphere is monitored.

➢ Onboard instrumentation

The IAGOS project described previously is only one of several projects which use aircraft on-board systems to measure the atmospheric composition. However, as it was mentioned previously, the IAGOS fleet which is equipped with instruments to measure atmosphere parameters consists only of 8 aircraft at the present time, which is a very small number. However, the measurements taken by these aircraft have a great value to evaluate the atmosphere composition and to predict weather events. Therefore, massively equipping aircraft with this type of instruments could provide an important breakthrough in this study field since the atmospheric composition measurements will be more accurate and reliable.

In addition, the aircraft should have not only this type of equipment available but also a communication system capable of broadcasting in real-time the measures taken by this equipment to all the stakeholders. Therefore, it will be required on-board advanced communication systems capable of collecting all the relevant data from the atmosphere, processing and sharing it with all the actors. In this way, weather predictions and forecasts will be more accurate and efficient. Taking this into account, it will be necessary to assure the integrity, reliability and availability of the on-board communication systems.

➢ Unmanned aircraft systems (UAS)

The availability of high-quality atmospheric measurements over extended spatial and temporal domains provide unquestionable value to meteorological studies. Traditional methods related to atmospheric measures include remote sensing instruments (radars, lidars, sodars and radiometers) or in-situ probes carried by balloons or manned aircraft. An alternative to these traditional approaches is the acquisition of atmospheric data through the use of highly capable unmanned aircraft systems (UAS) working in coordination with weather radar systems and other observing stations and platforms.

At present time, there is a key information gap between instruments on Earth's surface and on satellites. UAS could solve that gap revolutionizing the ability to monitor and understand the global environment, by operating at a lower altitude than aircraft and collecting data from dangerous or remote areas, such as the poles, oceans, wildlands, volcanic islands, and wildfires. Better data and observations would improve understanding and forecasts allowing better anticipation to dangerous weather events.

The use of unmanned aircraft systems (UAS) or unmanned aerial vehicles (UAVs) has become the most promising technology in atmospheric monitoring over the last few decades. UAS have the potential to become a major resource for scientific research and weather monitoring as they are capable of flying to any point in the vertical atmosphere and take air sample readings. They could also be used on routes which aircraft normally do not use and provide atmosphere data closer to the ground.

The capabilities of UAS have increased dramatically over the past decade, especially with improvements in autonomous flight performance. Moreover, the ability to send a UAS on a mission without the need for a pilot greatly expands the potential for extended measurements while simultaneously lowering the operational costs.

UAS could measure meteorological state parameters, such as wind, temperature, humidity, turbulence and other variables with great accuracy as well as rates of variation of these parameters. Over the last few decades, government agencies and private sector companies have employed UAS for surveying and atmospheric research, including hurricane research and volcanic plume sampling.UAS use for meteorological and other environmental monitoring began in the 1990s and became routinely used in the 2000s. Through several missions, the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) have proved their capability to be operated routinely to obtain science-quality data over remote atmospheric regions.

One recent example is a small unmanned aircraft system which is being developed by Black Swift Technologies for research in extreme environments. This UAS called SuperSwift XT (Figure 4.226) has been designed to collect data in harsh environments and to carry out in situ observations from inaccessible regions. One of its uses will be to explore volcanoes in order to improve air traffic management systems and the accuracy of ashfall measurements. This drone will be compound by sensors specifically designed to measure selected gases and atmospheric parameters, including temperature, pressure, humidity and 3D winds, as well as more advanced measurements, such as particle sizing and trace gases.

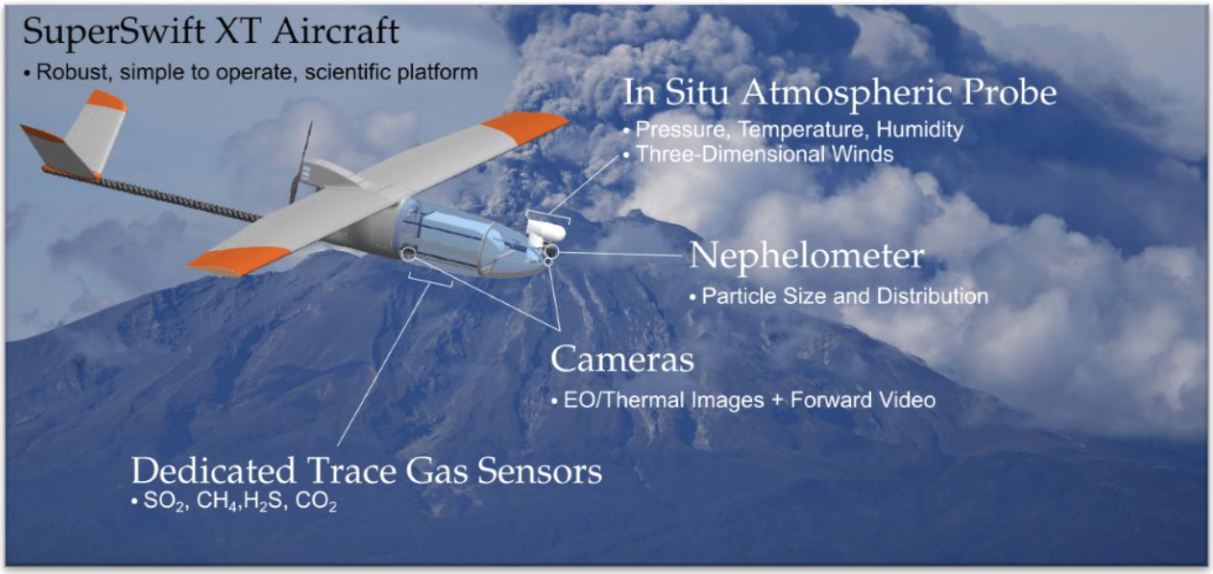


Figure 4.226: An UAV designed for environmental monitoring in hazardous conditions

The sensor and sensor coverage component will depend on the requirements of the systems and these requirements will depend on the application. A sensor will have to provide information about absolute, or process parameters at twice their natural temporal and spatial variability to ensure a representative natural data parameter field. Data processing architecture should be able to handle real-time, near terabyte per second data volumes, and data of multiple formats. It should also be able to accept and send secure communications. It will also require an onboard archive and ground station archive points to facilitate operational activities, ensure protection and minimize data loss.

In the following Table 4.53, it is shown a subset of the capabilities that an unmanned aircraft system could contain. However, the use of unmanned aircraft systems to monitor the atmosphere will have to address several risks:

- The drones will have to operate in airspace with other aircraft. Therefore, it will be necessary to develop procedures and rules so that both can operate without collision risks.For example, by the assurance of safe separation distances between unmanned aircraft and manned aircraft when flying in the national airspace;
- One of the unmanned aircraft main uses will be to operate in severe weather regions or in inaccessible areas. This will imply higher risks since they could suffer damage due to the severe conditions that will imply higher costs.

Function	Capability
Sensing	Atmospheric profiles surface to flight-level: air temperature, dewpoint temperature, 3D wind components, turbulent fluxes, static pressure, spectral irradiance, super cooled liquid water content. Atmospheric constituents and composition (aerosols, cloud, precipitation, trace gases, total water content) Surface characteristics (spectral reflectance, soil moisture, soil temperature profiles).

Data processing	Able to process terabytes of data per second; functional tools, decision support; calibration/validation
Software	Algorithms to yield required information, data logging, data processing

Table 4.53: Capabilities expected of an UAV designed for environmental monitoring

Due to a large amount of communications and data, unmanned aircraft could be exposed to security threats. Therefore, it will be required to assure data integrity and quality, data information dissemination and storage.

Despite the risks mentioned previously, using unmanned aircraft to monitor the atmosphere will have a lot of benefits that will allow developing better weather prediction models and forecasts. Although UAS are deployed operationally worldwide, they have not been integrated yet in weather monitoring operations at the present time. Using these systems on a global scale could support a great breakthrough in atmosphere monitoring. This is because as these systems become more common, it would allow to improve significantly weather modelling and forecasting.

➢ Cognitive intelligence for weather prediction: The weather company.

Using data from commercial aircraft and mobile phones to measure atmospheric parameters closer to the ground have been one of the most revolutionary ways to monitor theatmosphere in recent years. It has allowed disposing of more data to develop better weather predictions. This initiative has been carried out by the Weather Company.

The Weather Company is a weather forecasting and information technology company, which provides the world's leading technology platforms and services leveraging weather and related data. It provides critical weather information to a variety of business industries: aviation, energy, insurance and utility, as well as visualization software for broadcast media and digital platforms.

In addition, the company delivers critical weather data from around the globe to airlines worldwide, producing 26 billion individual forecasts daily. Meteorological insights are drawn from satellites, weather stations, planes, radar, terminal and enroute data.

Within the aviation sector, the Weather Company offers products that streamline aeronautical decision-making with accurate and highly reliable aviation and inflight weather data and decision support tools.

The objective of the weather company is mapping the entire atmosphere through data collected from:

- Sensors of aircraft 200 airlines/50,000 flights a day (pressure and wind speed).
- Drones and smartphones for measurements closer to the ground
- Satellites collect data from high above the globe

Therefore, the weather company develops weather forecasts through data provided by all type of sources such as mobile phones and aircraft. It is a new perspective which has not been considered previously and which has a lot of applications for the future.

For example, one of its major success is to predict turbulence, which is one of the main causes of loss of security and efficiency. The difficulty in predicting turbulence is a lack of high-quality data and workflow integration around turbulence information.

In response, The Weather Company launched WSI Total Turbulence, an initiative which provides a workflow integrated, end-to-end solution that improves certainty and reduces turbulence impacts and their associated

costs. WSI Total Turbulence delivers timely, precise and actionable turbulence alerts and guidance (Figure 4.227) through:

- On-board software that automatically and objectively measures and immediately reports turbulence events using existing aeroplane instrumentation. The sensors report every 15 minutes in non-turbulence situations and increase reporting to once every minute during a turbulence event.
- Cylinder shaped turbulence alerts that report precise location and severity in a visual manner that is easy to act upon.
- Constantly updated forecast models & alerts based upon integrated update feeds, the accuracy of which has gone through extensive validation testing.
- Distribution of alert information to all impacted operations and flight staff for consistent information sharing.

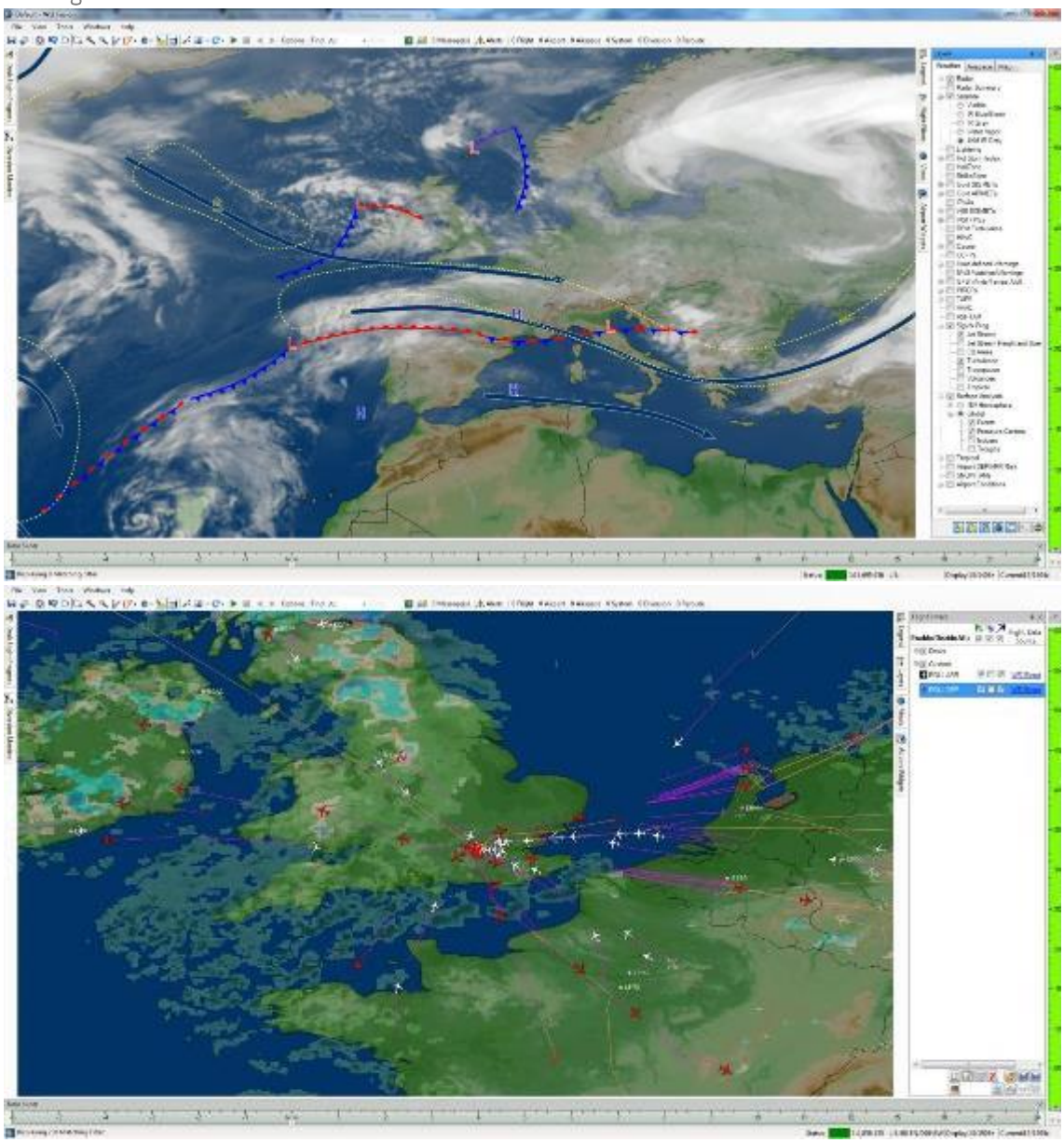


Figure 4.227: Weather alert available for aviation

By applying these techniques, it has been obtained beneficial results. For one airline using WSI Total Turbulence they experienced:

- A 50% reduction in Flight Attendant injuries;
- Year over year reduction in maintenance (40%);
- Captains accepting a higher number of planned flights;
- A decrease in turbulence encounters.

In conclusion, this type of weather forecasts will suppose a breakthrough in technology which will be enhanced in the future and it will allow developing better prediction models, decreasing damages caused to aviation due to weather conditions.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACAREChallenge 3 Goal 13**"Atmospheric Research, Weather and the Environment" achievements at 1st and 2nd stages of the researches on PARE Project are shown in Figure 4.228 grounding on the results of the 1st and 2nd year PARE reports (PARE D1.1, 2018, PARE D1.2, 2019).

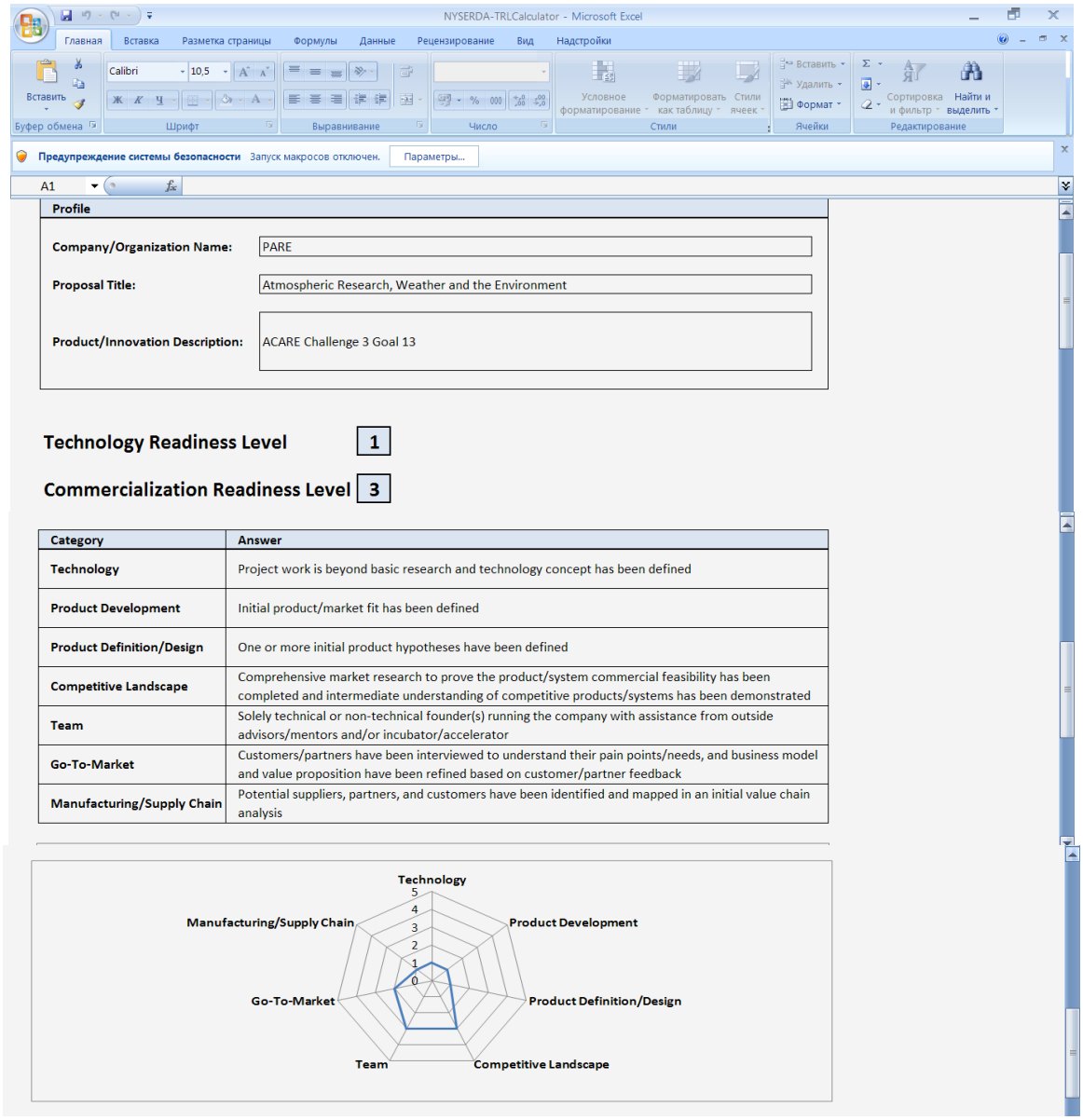


Figure 4.228: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 13 "Atmospheric Research, Weather and the Environment"

References

ACARE, 2016. Activity Summary 2014-15. [www.acare4europe.org]

Advancing Aerial Mobility: A National Blueprint**, 2020**. Committee on Enhancing Air Mobility, Aeronautics and Space Engineering Board, Division on Engineering and Physical Sciences. Washington, DC: The National Academies Press. (2020) [https://doi.org/10.17226/25646]

Airbus_Global_Market_Forecast_2017-2036_Growing_Horizons_full_book.pdf

Akatsuka, J., & Ishii, T., 2020. "System Noise Assessment of NASA Supersonic Technology Concept Aeroplane Using JAXA's Noise Prediction Tool." AIAA Scitech 2020 Forum. Presented at the AIAA Scitech 2020 Forum. https://doi.org/10.2514/6.2020-0265

Allen, C., Toulson, E., Edwards, T., Lee, T., **2012**. Application of a novel charge preparation approach to testing the autoignition characteristics of JP-8 and camelinahydroprocessed renewable jet fuel in a rapid compression machine. Combust. Flame 159 (9), 2780–2788, https://doi.org/10.1016/j.combustflame.2012.03.019

AR5 Synthesis Report: Climate Change **2014**. [https://www.ipcc.ch/report/ar5/syr/]

ASCENT Project 037, 2015. CLEEN II Technology Modeling and Assessment. Continuous Lower Energy, Emissions, and Noise (CLEEN) Program. Georgia Institute of Technology, 2015.

Astley R. J., 2014. Can technology deliver acceptable levels of aircraft noise? // Inter-noise 2014, Melbourne, Australia, 2014, paper 369. – 12 p.

ASTM International, 2014. ASTM D4054-14, Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives, ASTM International, West Conshohocken, PA, 2014, www.astm.org DOI: 10.1520/D4054-14

ASTM International, 2015. ASTM D7566-17b, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, ASTM International, West Conshohocken, PA, 2017, www.astm.org DOI: 10.1520/D7566-17B

ATAG, 2011. Air Transport Action Group. Beginner's guide to aviation biofuels. Available online: http://www.enviro.aero/Content/Upload/File/BeginnersGuide_Biofuels_WebRes.pdf (accessed on 8 August 2011).

Dimitriu D., Heyes G., Hooper P., 2018. Noise Impact Mitigation Priorities Report. EU , ANIMA, ID 769627, D2.2, 11th June 2018 [https://www.anima-project.eu].

Avinor. Electric Aviation, **2018**. https://avinor.no/en/corporate/community-and-environment/electric-aviation/electric-aviation

Baharozu, E., Soykan, G., Ozerdem, M. B. 2017. Future aircraft concept in terms of energy efficiency and environmental factors. Energy, Volume 140, Part 2, pages 1368-1377 (doi.org/10.1016/j.energy.2017.09.007)

Bailly, C., André, B., Castelain, T., Henry, C., Bodard, G., Porta, M. **2014** An analysis of shock noise components AerospaceLab Journal, Issue 7, pages AL07-06 (doi: 10.12762 / 2014.AL07-06)

Baklanov, V.S. 2010. Analysis of vibroacoustic processes in the turbojet engine and other power plant units based on the results of studies of the frequency characteristics of the "Engine-attachment-frame" system. Scientific notes of TsAGI, Volume XLI, No. 1, p. 78-85 (in Russian)

Basner M., C. Clark, A. Hansell, J.I. Hileman, S. Janssen, K. Shepherd, and V. Sparrow, Aviation noise impacts: State of the science, Noise Health 19(87):41-50, 2017. See generally https://www.noisequest.psu.edu/.

Beple, M. 2015. Innovations in the field of nacelles. SAFRAN, No.17, pages 34-35

Berger R., 2018. Aircraft Electrical Propulsion – The Next Chapter of Aviation. ROLAND BERGER LTD, 55 Baker Street, London W1U 8EW United Kingdom

Berton, J. J., Huff, D. L., Geiselhart, K., & Seidel, J., 2020. "Supersonic Technology Concept Aeroplanes for Environmental Studies". AIAA Scitech 2020 Forum. AIAA Scitech 2020 Forum. https://doi.org/10.2514/6.2020-0263

Boeing Current Market Outlook **2015-2034** [http://www.boeing.com/commercial/market/commercial-market-outlook/]

Boshell F., Masuyama T, 2020. Opportunities for renewable energy. Online Stocktaking Preview from IRENA – Int. Renewable ENergy Agency, ICAO, Montreal, 28 April 2020.

Brasseur, G. P., M. Gupta, B. E. Anderson, S. Balasubramanian, S. Barrett, D. Duda, G. Fleming, P. M. Forster, J. Fuglestvedt, A. Gettelman, R. N. Halthore, S. D. Jacob, M. Z. Jacobson, A. Khodayari, K.-N. Liou, M. T. Lund, R. C. Miake-Lye, P. Minnis, S. Olsen, J. E. Penner, R. Prinn, U. Schumann, H. B. Selkirk, A. Sokolov, N. Unger, P. Wolfe, H.-W. Wong, D. W. Wuebbles, B. Yi, P. Yang, and C. Zhou, **2015.** Impact of aviation on climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II, Bull. Amer. Met. Soc., 91, 461, doi: 10.1175/2009BAMS2850.1.

Bulusu V, Polishchuk V, Sedov L., 2017. Noise estimation for future large-scale small UAS Operations. INTER-NOISE and NOISE-CON Congress and Conference Proceedings, 2017; 864-871.

Burley C.L., Olson E.D., Thomas R.H., 2017. Hybrid wing body aircraft system noise assessment with propulsion airframe aeroacoustic experiments. International Journal of Aeroacoustics. Vol. 11, No. 3&4.4.16.2012. Accessed 1.10.2017

CAEP/8-WP/10. 2010. Report of the Independent Experts to CAEP/8 on the second NOx review & long term technology goals. London, 2009.

CAEP/9 Meeting, 2013. Report to CAEP by the Noise Technology Independent Expert Panel. *Novel aircraft noise technology review and medium and long term noise reduction goals.*

Chang CT, Lee CM, Herbon JT, Kramer SK, **2013**. NASA Environmentally Responsible Aviation Project Develops Next-Generation Low-Emissions Combustor Technologies (Phase I). J Aeronaut Aerospace Eng 2: 116. doi:10.4172/2168-9792.1000116

Cao W., Mecrow B. C., Atkinson G.J., Bennett J. W., Atkinson D. J., 2012. Overview of electric motor technologies used for more electric aircraft (MEA)," IEEE Trans. Ind. Electron., vol. 59, no. 9, pp. 3523–3531, 2012.

Chevagin, A.F. 2015. Integration of power plants on advanced aircraft. Aircraft engines of the XXI century, CIAM named after P.I. Baranov, Moscow, Russia

Christian A, Cabell R., 2017. Initial investigation into the psychoacoustic properties of small unmanned aerial system noise. 23rd AIAA/CEAS Aeroacoustics Conference, AIAA AVIATION Forum, 2017.

Coan P., 2016. ARMD Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft. Presented at Aeronautics R&T Roundtable, Washington DC.

Collin D., 2016. Overview of overview of aviation noise research effort supported by the European Union // ICAO Environmental Report 2016, p 38-41

CORE-JETFUEL Report Summary, 2016. http://cordis.europa.eu/result/rcn/192392_en.html

Craig L., 2006. Boeing Noise Technology.Los Angeles World Airports Community Noise Roundtable, 13 September 2006, Boeing.

Crighton D., 2007. Fan design and operation for ultra low noise // PhD Thesis, Uni. Of Cambridge, Dep.of Engineering, 2007 [http://silentaircraft.org/docs/dcphd.pdf]

Czech M.J., Thomas, R.H., Elkoby, R., 2012. Propulsion Airframe Aeroacoustic Integration Effects of a Hybrid Wing Body Aircraft Configuration, International Journal of Aeroacoustics, Volume 11, Number 3+4, 2012, pp. 335-368

Danner, F., Kendall-Torry, C. 2014. Effect of the blade tip modifications for unductedpropulsors on tip vortex-rotor interaction noise. Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A014, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-27134)

Delfs, J.W., Appel, Ch., Bernickey, P., Blechz, Ch., Blinstrubx, J., Heykena, C., Kumary P., Kutscherk, K., Lippitz, N., Lummer, M., Rossian, L., Savoni, L. **2017**. Aircraft and technology for low noise short take-off and landing. 35th AIAA Applied Aerodynamics Conference, Denver, Colorado

Dickson N., 2020. Setting the scene: Aviation in-sector CO_2 emissions reductions: trends and achievements. Aviation CO_2 reductions: Online Stocktaking Preview, 28 April 2020.

Dobrzynski W. M., 2005. Schoning B., Leung Choi Chow, Wood C. and C.Seror. 2005. *Design and testing of low noise landing gears*. AIAA 2005–3008, 11 th Aeroacoustics Conference, Monterey, May 2005.

Dobrzynski W., 2010. Almost 40 years of airframe noise research: what did we achieve? // Jour. Aircraft 2010;47(2):353–67.

Dobrzynski W, Chow LC, Guion P, Shiells D., 2002. Research into landing gear airframe noise reduction // AIAA-2002-2409, 2002.

Doroshenko E., Tereshchenko, Y., Lastivka, I., Tereshchenko, Y. **2017**. Calculation of sound power level of tandem axial fan. EasternEuropean Journal of Enterprise Technologies. Volume 6, N. 5–90. pages 8–12. (doi: 10.15587/1729-4061.2017.114038)

Doyle A., 2020. Coronavirus: plane-free skies spur research into warming impact of aviation [https://www.climatechangenews.com/2020/04/09/coronavirus-plane-free-skies-spur-research-warming-impact-aviation/]

Duran I., Moreau, S., Nicoud, F., Livebardon, T., Bouty, E., Poinsot, T. **2014** Combustion Noise in Modern Aero -Engines. AerospaceLab Journal, Issue 7, pages AL07-05 (doi: 10.12762 / 2014.AL07-05)

Dzikus N., Fuchte J., Lau A., Gollnick V., 2011. Potential for Fuel Reduction through Electric Taxiing // 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 2011.

EU Biofuels Annual 2019. GAIN Report Number: NL9022. 7/15/2019

European Aviation Safety Agency (**EASA**), European Environment Agency (**EEA**), **EUROCONTROL**, **2016**. European Aviation Environmental Report 2016. ISBN: 978-92-9210-197-8 doi: 10.2822/385503. Catalogue No.: TO-01-15-323-EN-N

European Aviation Safety Agency (**EASA**), European Environment Agency (**EEA**), **EUROCONTROL, 2019**. European Aviation Environmental Report 2019. ISBN: 978-92-9210-214-2 doi: 10.2822/309946. Catalogue No.: TO-01-18-673-EN-N [www.easa.europa.eu/eaer]

EC, 2008, Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003 87 EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community (OJ L 8, 13.01.2009, p. 3).

EEA, TERM 2014. Focusing on environmental pressures from long-distance transport: transport indicators tracking progress towards environmental targets in Europe, EEA Report No 7/2014, European Environment Agency, 2014.

EEA, TERM 2017, Transport and Environment Reporting Mechanism, European Environment Agency, 2017.

EC, 1996, Future noise policy, European Commission Green paper, COM 96 (540).

EC, 2002, Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise.

EEA, 2014, Noise in Europe, EEA Report No 10/2014.

EEA, 2010, Good practice guide on noise exposure and potential health effects, EEA Technical report No 11/2010.

Electrification of the Transport System, 2017. Studies and reports. Directorate-General for Research and Innovation. Smart, Green and Integrated Transport, 2017.

EU, 2014, Regulation (EU) 598/2014 of the European Parliament and the Council of 16 April 2014 on the establishment of rules and procedures with regard to the introduction of noise related operating restrictions at Union airports within a Balanced Approach and repealing Directive 2002/30/EC.

EU, 2018, European Semester – Europe's growth strategy and 2020 targets.

EEA, 2017, Trends and projections in Europe 2017, EEA Report No 17/2017.

EU, 2018, EU climate and energy framework for 2020, 2030 and 2050.

EC, 2011, White Paper, Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system, COM(2011) 144 final.

EEA, 2017, Air quality in Europe – 2017 report, EEA Report No 13/2017.

EEA, 2018, Greenhouse gas - data viewer.

EC, 2008, Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.

EU, 2016, EU Directive 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC new National Emission Ceilings Directive 206/2284.

European Aviation in 2040. CHALLENGES OF GROWTH. EUROCONTROL - **2018** (Edition 2).

Eury S., 2005. Research and Technology at Snecma to Ensure Sustained Development of Air Transportation. AIAA/AAAF Aircraft Noise and Emissions Reduction Symposium, May 24-26, 2005, Monterey, California, Snecma.

FAA (Federal Aviation Administration), **2011**. Special Airworthiness Information Bulletin: Semi-synthetic Jet Fuel. Federal Aviation Administration, Washington D.C., USA

Ferrante, P. Francescantonio, P., Hoffer, P.-A., Vilmin, S., Hirsch, Ch. **2014**. Integrated "CFD-Acoustic" computational approach to the simulation of aircraft fan noise. Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A009, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-26429)

Filippone, A. 2016 Development of a New Aircraft Noise Prediction Program. 16th AIAA Aviation Technology, Integration, and Operations Conference, pages 1-12, Washington (doi.org/10.2514/6.2016-3902)

Fleuti E., Maraini S., 2017. Taxi-Emissions at Zurich Airport," 2017. https://www.zurich-airport.com/the-company/noise-policy-and-the-environment/air-quality. [Accessed: 17-Jul-2019].

FORUM - AE, 2015. Mid - Term Synthesis. D4.14, Forum-AE Coordination & Support Action, FP7 – 605506.

Fregnani J.A.T.G., Mattos B. S., 2016. Aviation and Electrical Road Vehicles. Conference Paper, June 2016 [https://www.researchgate.net/publication/303902588]

Friedlingstein et al, 2019. Global Carbon Budget 2019. CDIAC.

Gan B., 2016. Aviation: the wings of (climate) change. Schroders: TalkingPoint. August 2016 [https://www.schroders.com/en/SysGlobalAssets/email/international/2016/2016-08-aviation-the-wings-of-climate-change.pdf]

Gettelman A., Chieh C.C., Jacobson M.Z., Cameron M.A., Wuebbles D.J., Khodayari A., **2017**. Coupled Chemistry Climate Effects from 2050 Projected Aviation Emissions., Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2017-218, 2017 [https://www.atmos-chem-phys-discuss.net/acp-2017-218/acp-2017-218.pdf]

GIACC, 2009. Global aviation CO_2 emissions projections to 2050, GIACC/4, Montréal, 25 to 27 May 2009.

Giangrande P., et al., 2019. Review, Challenges and Future Developments of Electric Taxiing Systems // [https://www.researchgate.net/publication/337638283], November 2019, DOI: 10.1109/TTE.2019.2956862.

Goldhammer M., 2011. The Next Decade in Commercial Aircraft Aerodynamics – A Boeing Perspective, Aerodays 2011, Madrid, Spain, 31 March 2011

Gorton S.A., 2018. NASA Revolutionary Vertical Lift Technology Project Research, Aircraft Noise and Emission Symposium, Long Beach, CA, February 27, 2018.

Greene D.L., 1992. Energy-efficiency improvement potential of commercial aircraft. Ann. Rev. Energy Environ. 1992, 17, 537-573.

Grewe V., et al., 2007. Climate impact of supersonic air traffic: an approach to optimize a potential future supersonic fleet – results from the EU-project SCENIC. Atmos. Chem. Phys., 7, 5129–5145, 2007 [https://doi.org/10.5194/acp-7-5129-2007]

Grewe V., et al., 2010. Estimates of the climate impact of future small-scale supersonic transport aircraft–results from the HISAC EU-project, Aeronaut. J. 114 (1153) (2010) 199.

Grewe V., Stenke A., Plohr M., Korovkin V., 2010. Climate functions for the use in multi-disciplinary optimisation in the pre-design of supersonic business jet, Aeronaut. J.114 (1154) (2010) 259–269.

Grimm, F., Ohno, D., Ewert, R., Dierke, J., Noll, B., Aigner, M., **2016** Broadband combustion noise simulation of the PRECCINSTA burner based on stochastic sound sources. Proceedings of ASME Turbo Expo 2016: Turbine Technical Conference and Exposition, pages V02AT04A004, ASME, Seoul, South Korea (doi: 10.1115 / GT2016-56124)

Grote M., Williams I., Preston J., 2014. Direct carbon dioxide emissions from civil aircraft // Atmospheric Environment vol. 95 (2014) 214–224, pp. 1352-2310 http://dx.doi.org/10.1016/j.atmosenv.2014.06.042 //

Guo Y., Thomas R. H., 2015. System noise assessment of hybrid wing body aircraft with open rotor propulsion. Journal of Aircraft.Vol. 52. 2015

Guynn, M., 2012. Open Rotor Propulsion Assessment for Advanced Single-Aisle Aircraft. NASA Fundamental Aeronautics Program Technical Conference, Renaissance Cleveland Hotel, Cleveland, 14 March 2012, Lecture

Haley Ph., 2006. Perspectives on noise&emissions reductions. Presentation, Aircraft Noise and Emissions Reduction Symposium (ANERS), Monterey, California, 24-26 May 2005.

Hall, C.A., Schwartz, E. and Hileman, J.I., 2009. 'Assessment of technologies for the Silent Aircraft Initiative', AIAA Journal of Propulsion and Power, 25(6), pp. 1153-1162

Hassan M., Pfaender H., Mavris D.N., 2017. Feasibility Analysis of Aviation CO2 Emission Goals Under Uncertainty // 17th AIAA Aviation Technology, Integration, and Operations Conference, June 2017.

Hassan M., Pfaender H., Mavris D.N., 2018. Probabilistic Assessment of Aviation CO2 Emission Targets // Transportation Research Part D Transport and Environment 63 August 2018.

Havrilesko, B.R., Hassan, M., Denney, R.K., Tai, J.C. **2014**. En Route Jet Aircraft Noise Analysis. AIAA / 3AF Aircraft Noise and Emissions Reduction Symposium, Atlanta, GA (doi.org/10.2514/6.2014-3163)

He, J.-C., and Y.-Q. Xu, 2012. Estimation of the aircraft CO_2 emissions of China's civil aviation during 1960–2009. Adv. Clim. Change Res., 3(2), doi: 10.3724/SP.J.1248.2012.00099

Heinemann P, et al, 2017. Advanced tube and wing aircraft for year 2050 timeframe. In: *55th AIAA aerospace sciences meeting*, Grapevine, TX, USA, 9–13 January 2017. Reston, VA: American Institute of Aeronautics and Astronautics.

Hendricks, E.S., Tong, M.T. 2012 Performance and Weight Estimates for an Advanced Open Rotor Engine. 48th AIAA / ASME / SAE / ASEE Joint Propulsion Conference & Exhibit, Atlanta, Georgia (doi.org/10.2514/6.2012-3911)

Henne P.A., 2005. Case for small supersonic civil aircraft, J. Aircr. 42 (3) (2005) 765–774.

Herbon J., Aicholtz J., Hsieh Shih-Yang, Viars Ph., Birmaher S., Brown D., Patel N., Carper D., Cooper C., Fitzgerald R., Pandalai R., Hong Z., **2017**. N+2 Advanced Low NO_x Combustor Technology. Final Report. NASA/CR—2017-219410

Hildebrandt, T., Thiel, P., Albert, S., Vilmin, S. **2014**. Applying an extended non linear harmonic method to a CROR configuration with emphasis on the acoustic signature. Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A001, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-25061);

Hileman J.I., Reynolds, T.G., Blanco, E. R., Law, Th. R., Thomas, S. **2007**. Development of Approach Procedures for Silent Aircraft. 45th AIAA Aerospace Sciences Meeting and Exhibit Special Session – Towards A Silent Aircraft, Reno, Nevada;

Holden J., Goel N., 2016. Fast-Forwarding to a Future of On-Demand Urban Air Transportation," San Francisco, CA, 2016.

Holland, M., Mann, M., Ralph, M., Owen, B., Lee, D., Horton, G., Dickson, N., Kollamthodi, S., 2011. A Marginal Abatement Cost Curve Model for the UK Aviation Sector. DfT Aviation MACC Study. Technical Report: Final. Department for Transport, London, UK

Horinouchi S., 2005. Conceptual Design of a Low Boom SSBJ, AIAA 2005-1018, 43rd AIAA Aerospace Sciences Meeting and Exhibit. Reno, Nevada, 10–13 January, 2005.

Hudda, N., Gould, T., Hartin, K., Larson, T. V., Fruin, S.A. **2014**. *Emissions from an international airport increase particle number concentrations 4-fold at 10 km downwind.* Environ. Sci. Technol. 48, 6628–6635. doi:10.1021/es5001566

Hupe J., 2020. Objectives of the ICAO Stocktaking process, Stocktaking Seminar and Online Stocktaking Preview. Aviation CO_2 reductions: Online Stocktaking Preview, 28 April 2020.

Huff DL, Henderson BS, Envia E., 2016. Motor noise for electric powered aircraft. Aeroacoustics Conference, 2016.

IATA, Fact Sheet Industry Statistics, 2017. http://www.iata.org/pressroom/ facts figures / fact sheets / Documents / fact-sheet- industryfacts.pdf, last cited: 20.04.2017

IATA Technology Roadmap, 2013. 4th Edition, June 2013.

Aircraft Technology Roadmap to 2050, 2018. IATA, 5th Edition, June 2018.

IATA FactSheet, 2019. Technology Roadmap for Environmental Improvement FactSheet, June 2019

ICAO 39th Assembly, 2016. Agenda Item 22: Environmental Protection – International Aviation and Climate Change – Policy, Standardization and Implementation Support/ ICAO'S CO2 STANDARD FOR NEW AIRCRAFT (Presented by the International Coalition for Sustainable Aviation (ICSA) [https://www.transportenvironment.org/sites/te/files/publications/wp_207_en%20ICSA%20CO2%20Standard.pdf]

ICAO Annex 16 to the Convention on International Civil Aviation — Environmental Protection: Volume I — Aircraft Noise; Volume II — Aircraft Engine Emissions; Volume III — Aeroplane CO_2 Emissions; Volume IV — Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), **2019**.

ICAO CAEP/7-IE/WG/3. 2007. Long Term Technology Goals for CAEP/7. WG3 and IE Chair presentation to CAEP/7, February, 2007.

ICAO CAEP/8-IP/11. 2010. Update on advances in emissions reduction technology: NO_X // Committee on Aviation Environmental Protection (CAEP), 8TH MEETING, Montréal, 1 to 12 February 2010

ICAO CAEP/9 Meeting. 2013. *Novel aircraft noise technology review and medium and long term noise reduction goals.* Report to CAEP by the Noise Technology Independent Expert Panel.

ICAO CAEP/10 Meeting. 2016. Agenda Item 5: CO2 Standard development/ Report of the WG3 CO2 Task Group (Presented by WG3 CO2 Task Group)

ICAO Circular 303-AN/176, 2004. Operational Opportunities to Minimize Fuel Use and Reduce Emissions

ICAO AN-Conf/13-WP/211, 2018. Emissions from supersonic aeroplanes. Thirteenth Air Navigation Conference, Montréal, Canada, October 2018.

ICAO CORSIA, 2019. Carbon offsetting and reduction scheme for international aviation () implementation plan. ICAO, 2019

ICAO CORSIA Eligibility Criteria, 2019. Emissions Unit Eligibility Criteria. ICAO, 2019.

ICAO CORSIA PACKAGE, 2019. Presented by GMTF co-Rapporteurs, ICAO, 2019.

ICAO Document 9184, Airport Planning Manual, Part 2 — Land Use and Environmental Control.

ICAO Document 9501, 2019. Environmental Technical Manual (Volumes I, II, III, and IV).

ICAO Document 9829, Guidance on the Balanced Approach to Aircraft Noise Management.

ICAO Document 9884, Guidance on Aircraft Emission Charges Related to Local Air Quality.

ICAO Document 9885, Guidance on the Use of Emissions Trading for Aviation.

ICAO Document 9888, **2007**. Review of Noise Abatement Procedure Research & Development and Implementation Results.

ICAO Document 9889, 2011. Airport Air Quality Manual.

ICAO Document 9911, Recommended Method for Computing Noise Contours around Airports.

ICAO Document 9950, Report on Voluntary Emissions Trading for Aviation (VETS Report).

ICAO Document 9951, Offsetting Emissions from the Aviation Sector.

ICAO Document 9963, Report of the Independent Experts on the Medium and Long Term Goals for Aviation Fuel Burn Reduction From Technology.

ICAO Document 9963, Report of the Independent Experts on the Medium and Long Term Goals for Aviation Fuel Burn Reduction From Technology.

ICAO Document 9988, Guidance on the Development of States' Action Plan on CO2 Emissions Reduction Activities. 3rd edition, **2019**. Reviews.

ICAO Document 10031 Guidance on Environmental Assessment of Proposed Air Traffic Management Operational Changes.

ICAO, Doc 10127, 2019. Final Report of the Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft.

ICAO Environmental Report 2016. AVIATION AND ENVIRONMENT. DESTINATION GREEN. 999 Robert-Bourassa Boulevard, Montreal, QC, Canada, H3C 5H7 [www.icao.int]

ICAO Environmental Report 2019. AVIATION AND ENVIRONMENT. DESTINATION GREEN. 999 Robert-Bourassa Boulevard, Montreal, QC, Canada, H3C 5H7 [www.icao.int]

ICAO Resolution A40-17, 2019. Consolidated statement of continuing ICAO policies and practices related to environmental protection – General provisions, noise and local air quality

ICAO Resolution A40-18, 2019. Consolidated statement of continuing ICAO policies and practices related to environmental protection – Climate change

ICAO Resolution A40-19, 2019. Consolidated statement of continuing ICAO policies and practices related to environmental protection – Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

Innovation through evolution, 2019. [https://www.rolls-royce.com/innovation/advance-and ultrafan.aspx#background]

Isikveren A.T., Sizmann A., Hornung M., 2011. Realising Flightpath 2050: Initial Investigation of Potential Technological Solutions, SAE 2011 AeroTech Congress and Exhibition, Toulouse, France, 2011.

Jensen L., Thomas J., Brooks C., Brenner M., Hansman R.J.**, 2017**. Analytical Approach for Quantifying Noise from Advanced Operational Procedures. Twelfth USA/Europe Air Traffic Management Research and Development Seminar, 2017.

Johnson W., Silva C., 2018. Observations from Exploration of VTOL Urban Air Mobility Designs. October 2018

Johnson W., Silva C., Solis E., 2018. Concept Vehicles for VTOL Air Taxi Operations AHS Technical Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, January 16-19, 2018.

Kahn Ribeiro, S., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D., Lee, D.S., Muromachi, Y., Newton, P.J., Plotkin, S., Sperling, D., Wit, R., Zhou, P.J., 2007. Transport and its infrastructure. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change **2007**: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA

Khaletsky Yu.D. 2014. ICAO: a new standard for the noise of civil aviation aircraft. – Dvigatel (engine), No. 2 (92), p. 8-11 (in Russian)

Khaletsky Yu.D., Korzhnev V.N., Pochkin Ya.S. 2016. Influence of the add stages design features on the generation of the aircraft engine fan tonal noise. Herald of the Samara University. Aerospace engineering, technology and machine building. Machine building and power engineering, V. 15, No. 3, p.99 -108 (doi: 10.18287 / 2541-7533-2016-15-3-99-108) (in Russian)

Khaletsky Yu.D., Shypov R.A. 2010. Acoustic efficiency of combined noise silencers for turbojet bypass engine fans. Environmental problems of aviation, p. 39-58 (in Russian)

Khammash L., Mantecchini L. Reis V., 2017. Micro-simulation of airport taxiing procedures to improve operation sustainability: Application of semi-robotic towing tractor," 5th IEEE Int. Conf. Model. Technol. Intell. Transp. Syst. MT-ITS 2017 - Proc., pp. 616–621, 2017.

King, D., Inderwildi, O., Carey, C., Santos, G., Yan, X., Behrendt, H., Holdway, A., Owen, N., Shirvani, T., Teytelboym, A., **2010**.Future of Mobility – Roadmap Ways to Reduce Emissions while Keeping Mobile. Smith School of Enterprise and the Environment, Oxford, UK

Knobloch, K., Fischer, A., Bake, F., Enghardt, L., Busse-Gerstengarbe, S. **2014** Full-scale tests on APU noise reduction. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A011, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-26803)

Koch L. , 2017. Danielle, Bonacuse, Kuczmarski, Johnston, Miller, Jones, "The development of acoustic absorbers that mimic assemblies of natural reeds: Progress Report 1," NASA TM-2017-219438, 2017.

Kohlhaas, M., Carolus, T.H. 2014. Acoustic minimization of rotor-stator interaction noise of axial fans by trailing-edge blowing.Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A002, ASME, Düsseldorf, Germany (doi: 10.1115/GT2014-25113);

Kroo I., 2005. Unconventional con fi gurations for e ffi cient supersonic fl ight, VKI Lect. Ser. Innov. Config. Adv. Concepts Future Civ. Aircr. (2005).

Kröger, G., Schnell, R., Humphreys, N. D. 2012. Optimised Aerodynamic Design of an OGV With Reduced Blade Count for Low Noise Aircraft Engines. ASME Turbo Expo 2012: Turbine Technical Conference and Exposition. Volume 8: Turbomachinery, Parts A, B, and C, pages 407-418, Copenhagen, Denmark (doi:10.1115/GT2012-69459)

Lee, D.S., Fahey, D.W., Forster, P.M., Newton, P.J., Wit, R.C.N., Lim, L.L., Owen, B., Sausen, R., **2009**. Aviation and global climate change in the 21st century. Atmos. Environ. 43 (22–23), 3520–3537 doi:10.1016/j.atmosenv.2009.04.024;

Lee, D.S., Pitari, G., Grewe, V., Gierens, K., Penner, J.E., Petzold, A., Prather, M.J., Schumann, U., Bais, A., Berntsen, T., **2010**. Transport impacts on atmosphere and climate: aviation. Atmos. Environ. 44 (37), 4678–4734, doi:10.1016/j.atmosenv.2009.06.005;

Lee, J.J., Lukachko, S.P., Waitz, I., 2004. Aircraft and Energy Use; Academic Press: San Diego, CA, USA, 2004; Volume 1, pp. 29-38.

Lee J.J., 2010. Analyzing Effective Environmental Policy-Making Process and Evidence from Aviation Sector. In Handbook of Environmental Policy; Nova Science Publishers, Inc.: Hauppauge, NY, USA.

Lee, Ph., 2012. Research and Development of Low-Emissions Combustor Concepts and Associated Fuel Control Valves: Gen-2 Lean Direct Injection System (LDI-2) // Quarterly Report (Unlimited Rights Version) 6-29-2012, Contract. NNC11CA17C

Leeham, 2017. Airbus / Boeing production rates through 2020, URL: https://leehamnews.com/2015/02/03/airbusboeingproduction-rates-forecast- through-2020 / last cited: 20.04.2017

Leylekian, L., Lebrun, M., Lempereur, P. 2014. An Overview of Aircraft Noise Reduction Technologies. AerospaceLab Journal, Issue 7, pages AL07-01 (doi: 10.12762/2014.AL07-01)

Liebhardt B., 2011. An Analysis of the Market Environment for Supersonic Business Jets, Proceedings of the Deutscher Luftund Raumfahrtkongress (DLRK), Bremen, Germany, January 2011.

Liu, D., 2010. An Introduction to Civil Aviation (in Chinese). China Civil Aviation Publishing House, 245 pp.

Los Angeles World Airports, 2010. Aircraft Noise Abatement Operating Procedures and Restrictions, in LAX Rules and Regulations, no. September, Los Angeles, CA, 2010.

Luè A., et al., 2016. Future priorities for a climate-friendly transport: A European strategic research agenda toward 2030 // Journal International Journal of Sustainable Transportation, Vol. 10, Iss. 3, 2016.

Macintosh A., Wallace L., 2009. International aviation emissions to 2025: Can emissions be stabilised without restricting demand? Energy Policy 37 (2009) 264–273.

Madden P., 2005. Outlook for Medium Term Technologies, Presentation, 2006, Rolls-Royce.Flight, 2005, 15-21/111, v. 167, N 4976, p. 27.

Maglieri D.J., et al., 2014. Sonic Boom Six Decades of Research. NASA SP-2014-622, Langley Research Center, Hampton, Virgina, 2014.

Maldar, A., Arokkiaswamy, A., Gemson, R.M.O., Kumar, V.R.S **2008**. Aerodynamic Sound Reduction for Silent Aircraft. 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada; Grahamn, W.R., Hall, C.A., Morales, V. 2014 The potential of future aircraft technology for noise and pollutant emissions reduction. Transport Policy, Volume 34, pages 36–51 (doi :10.1016/j.tranpol.2014.02.017)

Mamaiev, V.K., Vlasov, E.N. 2009. Dependence analysis for the evaluation of noise of centrifugal impeller machines. Herald of the RUDN, series Engineering studies, No. 2, p. 106-113 (in Russian)

Medviediev, V.V., Timko, O.S. 2012 Comparative analysis of methods for reducing the noise of an aircraft engine exhaust jet. Scientific herald of the Moscow State Technical University, No. 179, p. 57-62 (in Russian)

Matthews D., Lee D.S. Fahey D., Fuglestvedt J.S., 2020. Climate change and aviation - Aviation CO_2 reductions: Online Stocktaking Preview from CICERO and IPCC Vice Chair Working Group I, ICAO, Montreal, 28 April 2020.

Miake-Lye R., et al. **2016**. White Paper on air quality aviation impacts on air quality: state of the science // ICAO Environmental Report 2016, p 75-80

Mincu, D.C., Manoha, E. 2014. Numerical and Experimental Characterization of Fan Noise Installation Effects.AerospaceLab Journal, Issue 7, pages AL07-08 (doi : 10.12762/2014.AL07-08)

Morioka N., Takeuchi M., Oyori H., 2014. Moving to an All-Electric Aircraft System // IHI Enginnering Review, vol. 47, No. 1, 2014.

Moshkov, P.A., Samokhin, V.F. 2016 Evaluation of the influence of the blades number and diameter on the propeller noise. herald of the Samara University. Aerospace engineering, technology and machine-building, Vol. 15, No. 3, p. 25-34. (doi: 10.18287 / 2541-7533-2016-15-3-25-34) (in Russian)

Nae, C. 2014 Advanced Aerodynamic Technologies for Future Green Regional Aircraft. INCAS BULLETIN, Volume 6, Special Issue 1, pages 99 – 110 (doi: 10.13111/2066-8201.2014.6.S1.11

NAP Report 23490, 2016. Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. PDF is available at SHARE [http://nap.edu/23490]

Nark et al., 2016. Further Development and Assessment of a Broadband Liner Optimization Process. 22nd AIAA/CEAS Aeroacoustis Conference; 30 May - 1 Jun. 2016; Lyon; France

National Research Council, 2002, For Greener Skies: Reducing Environmental Impacts of Aviation, The National Academies Press, Washington, D.C., [https://www.nap.edu/read/10353/chapter/1#ii].

Nickol, C., Haller, W., 2016. Assessment of the Performance potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project, 2016

Ninian, D.; Dakka, S.M., 2017. Design, Development and Testing of Shape Shifting Wing Model. Aerospace 2017, 4, 52.doi:10.3390/aerospace4040052; [www.mdpi.com/journal/aerospace]

Noh et al., 2016. The adaptation of sustainable biojet fuels and its effect on aircraft engine maintenance // AEROTECH VI - Innovation in Aerospace Engineering and Technology, IOP Conf. Series: Materials Science and Engineering 152 (2016) 012043 doi:10.1088/1757-899X/152/1/012043

Nolte P., et al., 2012. Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency. 3rd Air Transport and Operations Symposium (ATOS), Delft, Netherlands, 17 - 19 June 2012 [https://www.researchgate.net/publication/259895290]

Nordwall, G., Demeulenaere, A., Ferrante, P. 2014 Acoustic design and validation of radial inflow turbine. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A004, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-25935)

NSTC2010, 2010. National Aeronautics Research and Development Plan. NATIONAL SCIENCE AND TECHNOLOGY COUNCIL, WASHINGTON, D.C. 20502, February 2, 2010

Padalkar R., 2017. Global commercial aircraft fuel burn and emissions forecast: 2016 TO 2040. Blacksburg, Virginia. 2017

Panda, J., 2005 Identification of the noise sources in high speed. 11th AIAA / CEAS Aeroacoustics Conference, pages AIAA 2005-2844, Monterey, California (doi.org/10.2514/6.2005-2844)

PARE D1.1 2018. State-of-the-art Flightpath 2050 goals**.** Deliverable under WP1 of the PARE project, EC Grant agreement N° 769220, Horizon 2020, 29-05-2018

PARE D1.2 2019. State-of-the-art Flightpath 2050 goals**.** Deliverable under WP1 of the PARE project, EC Grant agreement N° 769220, Horizon 2020, 29-05-2018

Parker R., Lathoud M., 2010. Green aero-engines: technology to mitigate aviation impact on environment // //SPECIAL ISSUE PAPER Proc. I MechE Vol. 224 Part C: J. Mechanical Engineering Science, January 12, 2010, Special Issue Paper 529 //DOI: 10.1243/09544062JMES1515

Penner, J.E. et al, 1999. Aviation and the Global Atmosphere, A Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Perullo, Ch.A., Tai, J.C.M., Mavris, D.N. 2013. Effects of Advanced Engine Technology on Open Rotor Cycle Selection and Performance. Journal of Engineering for Gas Turbines and Power, Volume 135, pages 071204 (doi: 10.1115 / 1.4024019)

Piatunin K.R., Arkharova N.V., Remizov A.E. 2014. Numerical simulation of the tonal noise of a bypass turbojet engine fan stage. Herald of the Samara State Aerospace University, No. 5 (47), part 3, p. 60-65 (in Russian)

Pietremont N., Deremaux Y., 2005. Executive public summary of the three preliminary aircraft con fi guration families, HISAC Publ. Act. Rep. (2005).

Ploetner, K. O., Rothfeld R., Urban M., Hornung M., Tay G., Oguntona Oluwaferanmi, **2017**. Technological and Operational Scenarios on Aircraft Fleet-Level towards ATAG and IATA 2050 Emission Targets; AIAA AVIATION Forum, 5-9 June 2017, Denver, Colorado 17th AIAA Aviation Technology, Integration, and Operations Conference

Polacsek, C., Barrier, R., Kohlhaas, M., Carolus, T., Kausche, P., Moreau, A., Kennepohl, F. **2014.** Turbofan Interaction Noise Reduction Using Trailing Edge Blowing: Numerical Design and Assessment and Comparison with Experiments. AerospaceLab Journal, Issue 7, pages AL07-03 (doi : 10.12762/2014.AL07-03);

Pratt & Whitney, 2012. PurePower Family of Engines, Document No.: S16154-F.06.12,Pratt & Whitney, East Hartford, CT, USA,–URL: http://www.purepowerengine.com,URL: https://www.pw.utc.com/Content/PurePowerPW_1000G_Engine/pdf/B-1-1_purepower_brochure.pdf]

Prociw, A., Ryon, J.,Goeke J., 2012. Low NO_x Combustion Concepts in Support of the NASA Environmentally Responsible Aircraft Program, GT2012-68426, Proceedings of ASME Turbo Expo 2012, June 11-15, 2012

Randt N. P., Jessberger C., Ploetner K.O., 2015. Estimating the Fuel Saving Potential of Commercial Aircraft in Future Fleet- Development Scenarios; AIAA Aviation 2015 Conference, Dallas, USA, 2015

Redonnet, S. 2014. Aircraft Noise Prediction via Aeroacoustic Hybrid Methods Development and Application of Onera Tools over the Last Decade: Some Examples. AerospaceLab Journal, Issue 7, pages AL07-07 (doi: 10.12762 / 2014.AL07-07)

Rizzi SA, Palumbo DL, Rathsam J, Christian AW, Rafaelof M., **2017**. Annoyance to noise produced by a distributed electric propulsion high-lift system. 23rd AIAA/CEAS Aeroacoustics Conference, AIAA AVIATION Forum, 2017.

Rossikhin, A., Pankov, S., Brailko, I., Mileshin, V. **2014**. Numerical investigation of high bypass ratio fan tone noise. Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A007 Düsseldorf, Germany (doi: 10.1115 / GT2014-26354)

Royal Aeronautical Society, 2005. 'Air Travel – Greener by Design', Report of the Science & Technology Sub-Group, Royal Aeronautical Society, July 2005

Ruf Ch. 2013 Airport Local Air Quality. Zurich Airport Regional Air Quality Study, 2013. [https://www.zurich-airport.com/~/media/flughafenzh/dokumente/das_unternehmen/laerm_politik_und_umwelt/luft/2013_localairquality_e_final.pdf]

Rybinskaya, L.A., Bul'bovich, R.V., Kychkin, V.I. 2017. Effectiveness of methods for turbulent jets noise reduction. Herald of PSTU. Aerospace Engineering, No. 48, c.104-118 (doi: 10.15593 / 2224-9982 / 2017.48.10) (in Russian)

Safran and aviation's electric future, 2019. Press Kit 2019 Paris Air Show. [www.safran-group.com]

SciCom, 2019. Next Decade European Aeronautics Research Programme (2020-2030). A paper prepared by the Clean Sky Scientific Committee (SciCom) for submission to the Clean Sky Joint Undertaking (CSJU) 26 May 2019 [http://prof.nau.edu.ua/wp-content/uploads/2019/08/Next-decade-aeronautics-research-SciCom-2019.pdf]

Schilling T., Rötger., T, Wicke, K. 2016. AIRCAT Assessment of the Impact of Radical Climate-Friendly Aviation Technologies. Hamburg; URL: [http://elib.dlr.de/106658/1/2016_GreenerAviation_Paper_AIRCAT_20160906.pdf]

Schilling Th., 2016. Assessment of the Impact of Radical Climate-Friendly Aviation Technologies. DLR Lufttransportsysteme, Hamburg.

Senzig DA, Marsan M, Downs RS, Hastings AL, Cutler CJ, Samiljan RW**., 2018**. UAS noise certification and measurements status report. FAA Technical Report DOT-VNTSC-FAA-18-01.

Serrano, A., Fernández, J.R. 2014 Effect of airfoil clocking on noise of LP turbines. Part II: Modal structure analysis. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A003, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-25602)

Sgadlev, V.V. 2009. Optimization of the blades number of the contra-rotation fan stage, in terms of noise reduction in the source. Scientific herald of the Moscow State Technical University, No. 147, p. 136-141 (in Russian)

Shmyrov V., Merkulov V., Loginov V., 2020. Principle of modernization of the aircraft An-148, An-158, and An-178 for improving their fuel efficiency and increasing competitiveness // Eastern-European Journal of Enterprise Technologies, Vol 3, No 1 (105) (2020). – pp. 6-16.

Simoes A.F., Schaeffer R., 2005. The Brazilian air transportation sector in the context of global climate change: CO2 emissions and mitigation alternatives. Energy Convers. Manag. 2005, 46, 501-513.

Solonin V.I., KhaletskyYu. D., 2010. Ways to achieve advanced noise requirements for civil aviation aircraft. Environmental problems of aviation, p. 11-38 (in Russian)

Song, S.-K., Shon, Z.-H., 2012. Emissions of greenhouse gases and air pollutants from commercial aircraft at international airports in Korea. Atmos. Environ. 61 (61), 148–158

Strategic Research & Innovation Agenda 2017. Update, Vol. 1. [https://www.dlr.de/dlr/Portaldata/1/Resources/documents/2017/acare-strategic-research-innovation-volume-1-v2.7-interactive.pdf]

Sustainable Aviation Noise Road-Map, 2018 [www.sustainableaviation.co.uk]**.**

Sustainable Aviation Progress Report 2015-2017, 2018 [www.sustainableaviation.co.uk].

Sustainable Aviation Decarbonisation Road-Map: A path to net zero. A plan to decarbonise UK aviation, **2020**, [www.sustainableaviation.co.uk].

Szodruch, J., Grimme, W., Blumrich, F., Schmid, R. **2011**. Next generation single-aisle aircraft - Requirements and technological solutions. Journal of Air Transport Management, Volume 17, pages 33–39 (doi.org/10.1016/j.jairtraman.2010.10.007)

Tan, Ch.H., Voo, K.S., Siauw, W.L. 2014 CFD analysis of the aerodynamics and aeroacoustics of the NASA SR2 propeller. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A010, ASME, Düsseldorf, Germany (doi: 10.1115/GT2014-26779)

Tariq M., Maswood A.I., Gajanayake C. J., Gupta A.K., **2017**. IET Electr. Syst. Transp., 2017, Vol. 7 Iss.2, pp 93-103

TaxiBot-International, 2018. Available: http://www.taxibot-international.com/. [Accessed: 16-May-2018].

Theodore CR. , 2018. A summary of the NASA design environment for Novel Vertical Lift Vehicles (DELIVER) project. AHS International Technical Meeting on Aeromechanics Design for Transformative Vertical Flight, 2018.

Timushev S.F., Gavriliuk V.N., Aksenov A.A., Klimenko D.V. **2017**. Simulating the source and acoustic field of impeller machines tonal noise. Noise Theory and Practice, Volume 3, No. 3, p. 19-30 (in Russian)

Tsilingiridis, G., 2009. Aircraft air pollutant emissions in Greek airports. Global Nest J. 11 (4), 528–534

UAM MARKET STUDY, 2018. Technical Outbrief. Presented to: National Aeronautics and Space Administration – Aeronautics Research, Mission Directorate, OCTOBER 19, 2018

US DOT FAA 14 CFR Parts 21 and 36, 2020. Noise Certification of Supersonic Aeroplanes. [https://www.faa.gov/about/office_org/headquarters_offices/apl/noise_emissions/aircraft_noise_levels/media/2120-AL_29_Noise_Cert_Supersonic_NPRM_033020.pdf]

US Postal Service, Office of Inspector General, 2016. Public perception of drone delivery in the United States. RARC report RARC-WP-17-001, 2016.

Vaishnav P., 2014. Costs and Benefits of Reducing Fuel Burn and Emissions from Taxiing Aircraft // Transp. Res. Rec., vol. 2400, no. 1, pp. 65–77, 2014.

Vascik P. D., 2017. Systems-Level Analysis of On Demand Mobility for Aviation. Massachusetts Institute of Technology, 2017.

Vascik P. D., Hansman R. J., 2017. Constraint Identification in On-Demand Mobility for Aviation through an Exploratory Case Study of Los Angeles. 17th AIAA Aviation Technology, Integration, and Operations Conference, 2017.

Volkov S.A., Gorbatko A.A., Khaletsky Y.D., 2010. Review of the existing and anticipated foreign requirements for civil aviation engines on limitation of harmful substance emissions / // Ecological problems of aviation. CIAM works №1347 - Moscow: TORUS PRESS, 2010. - P. 234-246

Waitz I.A., Lukachko S.P., Lee J.J., 2005. Military aviation and the environment: Historical trends and comparison to civil aviation. J. Aircr. 2005, 42, 329-339.

Walkden F., 1958. The shock pattern of a wing-body combination, far from the flight path, Aeronaut. Q. 9 (02) (1958) 164–194.

Wang, P., Zangeneh, M. 2014. Aerodynamic and aeroacoustic optimization of a transonic centrifugal compressor. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A012, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-26813)

Warwick G., 2017. "Lockheed, NASA Advanced Airlifter Tests Validate Fuel Savings." Aviation Week and Space Technology. Vol. 177, No. 348.31.2015. Accessed 1.25.2017. http://web.b.ebscohost.com/bsi/detail/detail?sid=37d5d20c-566d-49f7-a4f514932d963d51%40sessionmgr104&vid=0&hid=116&bdata=JnNpdGU9YnNpLWxpdmU%3d#AN=110240912&db=bth

Weiyi Fan, Yifei Sun, Tianle Zhu, Yi Wen, 2012. Emissions of HC, CO, NO_x, CO_2, and SO_2 from civil aviation in China in 2010. Atmospheric Environment 56 (2012) 52–57/ [doi:10.1016/j.atmosenv.2012.03.052]

Welge H., Nelson C., Bonet J., 2010. Supersonic vehicle systems for the 2020–2035 timeframe, AIAA 2010-4930, 28th AIAA Applied Aerodynamics Conference, Chicago, Illinois, 28 June–1 July, 2010.

Whitham G., 1952. The flow pattern of a supersonic projectile, Commun. Pure Appl. Math. 5 (3) (1952) 301–348.

Woodrow Bellamy III, 2019. Public Perception of Urban Air Mobility Shaped by Noise, Safety Avionics International, February 12, 2019

Whurr J., 2013. Future Civil Aeroengine Architectures & Technologies Rolls-Royce, 2013 [http://www.etc10.eu/mat/Whurr.pdf]

X-NOISE, 2015. Evaluation of Progress Towards ACARE Noise Targets // Aviation Noise Research Network and Coordination, X-NOISE EV, Project Number 265943, Deliverable D06.31, Date of preparation: June 2015

Xiaowen Yang, Shuiyuan Cheng, Jianlei Lang, Ran Xu, Zhe Lv, **2018**. Characterization of aircraft emissions and air quality impacts of an international airport// // J. Environ. Sci. (2018), [https://doi.org/10.1016/j.jes.2018.01.007]

Yedavalli P., Mooberry J., 2018. An Assessment of Public Perception of Urban Air Mobility. Airbus UTM. Defining Future Skies.

Zamtforth, B.S. 2012. Open-rotor engine in the light of toughening the requirements for aviation ecology. Proceedings of the Samara Scientific Center of the Russian Academy of Sciences, Vol. 14, No. 6, p. 307-308 (in Russian);

Zante, D.E., Envia, E. 2014. Prediction of the aero-acoustic performance of open rotors. Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, pages V02AT41A008, ASME, Düsseldorf, Germany (doi: 10.1115 / GT2014-26413)

Zaporozhets O., Isaienko V., Synylo K., 2020. PARE preliminary analysis of ACARE FLIGHTPATH 2050 environmental impact goals. Aerospace Europe Conference AEC 2020 Conference, Bordeaux, France, 23-25 February 2020, Paper 558, 12 p.

Zawodny NS, Christian A, Cabell R., 2018. A summary of NASA research exploring the acoustics of small unmanned aerial systems. AHS International Technical Meeting on Aeromechanics Design for Transformative Vertical Flight, 2018.

Zhou, L.-P., 2010. The development of China's civil aviation industry: The problems and the counter-measures. China Civil Aviation (in Chinese), (4), 28–30

Zhoujie Lyu, Martins Joaquim R. R. A., 2015. Aerodynamic Shape Optimization of an Adaptive Morphing Trailing-Edge Wing. Journal of Aircraft, Vol. 52, No. 6 (2015), pp. 1951-1970. https://doi.org/10.2514/1.C033116

Zimcik, D.G. 2004 Active control of aircraft cabin noise. AVT 101 symposium on Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion, Prague, Czech Republic