PARE

PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

Perspectives for Aeronautical Research in Europe

2018 Report

CHAPTER 4

Protecting the Environment and the Energy Supply

Final Version

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Chapter 4 - Protecting the Environment and the Energy Supply

This set of 5 goals consists of reductions of noise and emissions (section 4.1), emissions free taxying (section 4.2), recycling enabled by design (section 4.3), alternative fuels (section 4.4) and atmospheric research (section 4.5).

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-JetFuel, which relates to alternative aviation fuels. In 2015 ACARE published a 2014/2015 activity update. This 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.

Politically, there is a shared awareness 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. Aviation environmental impacts include gaseous emissions and noise issues. Hardly any technical solution is able to 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:

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 CO2 emissions from air transport:

- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020;
- A cap on net aviation CO2 emissions from 2020 (carbon-neutral growth);
- A reduction in net aviation CO2 emissions of 50% by 2050, relative to 2005 levels.

To achieve these targets, all stakeholders agreed to closely work together along 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 A39-1, ICAO Resolution A39-2, ICAO Resolution A39-3], providing in such way very ambitious policy for environment protection from civil aviation impact and for the sustainable growth of aviation as 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) for the purpose of assisting in the further development of Standards, Recommended Practices and Procedures and/or guidance material on aircraft noise and engine emissions to assist States in implementing them in efficient way.

4.1 Reduction of Noise and Emissions

**** Flightpath 2050 goal 9: "In 2050 technologies and procedures available allow a 75% reduction in CO2 emissions per passenger km and a 90% reduction in NOx 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.

4.1.1 Engine Noise for Turbofans and Propfans

Since the start of the jet age enormous progress has been made in lowering noise levels and reducing the noise footprint per aircraft movement. Some of this progress has been offset by air traffic growth that can lead to increased total noise exposure unless noise reductions continue. 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 it limits for by-pass ratios (BPR) in the range 15-20.

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. 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.

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 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 A39-1]. The initial SRA1 approach presiding over the definition the ACARE 2020 noise targets remains valid (Figure 4.1), 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.

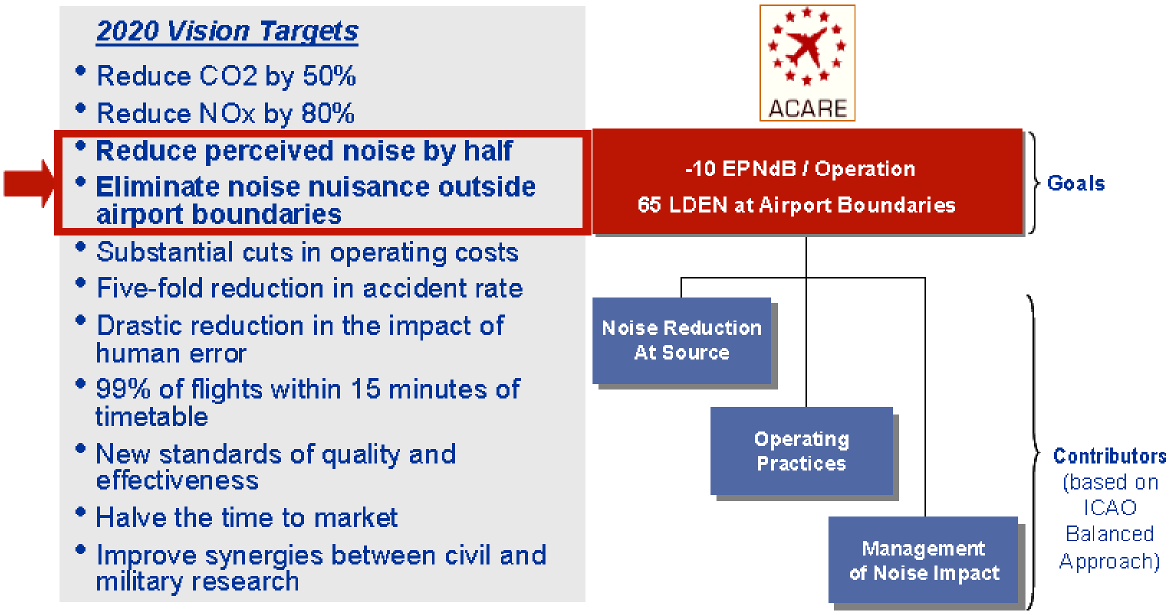


Figure 4.1 - ACARE SRA 1: Noise Goals for Fixed-Wing Aircraft

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 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), based:

- On the internationally recognised **Technology Readiness Level scale** (Figure 4.2), that allows to keep track of the situation of individual technologies identified in the SRA1.
- On a dedicated process, called **Technology Evaluator**, involving a predictive model with capability to roll up the benefits of individual technologies at solution level and establish the progress achieved globally, including operational aspects.

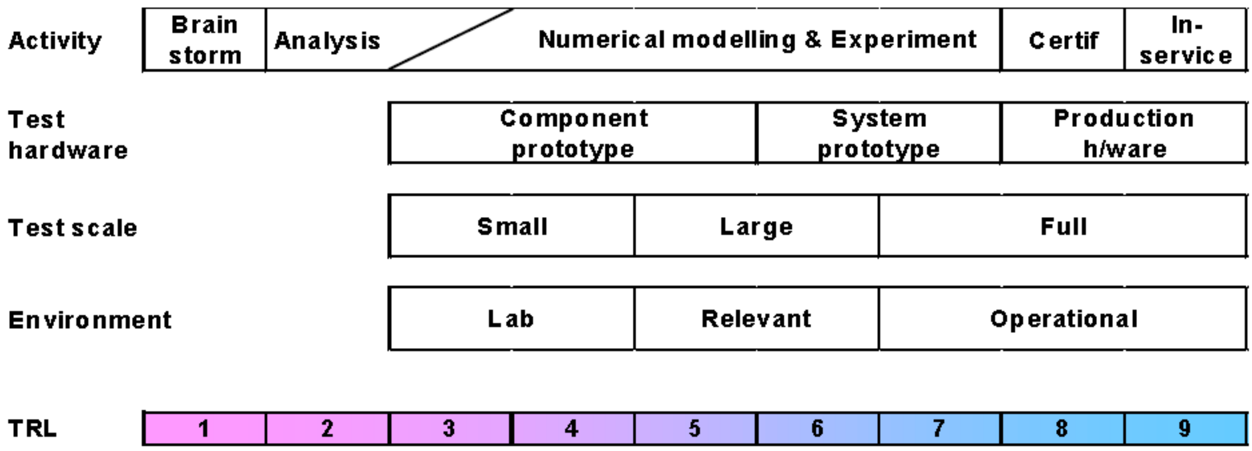


Figure 4.2 - Technology Readiness Level Classification (TRL) used for solutions assessment

An approach by consensus based on expert's judgement, assessment of the TRL situation and results from the technology evaluation exercises has 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 4.3).

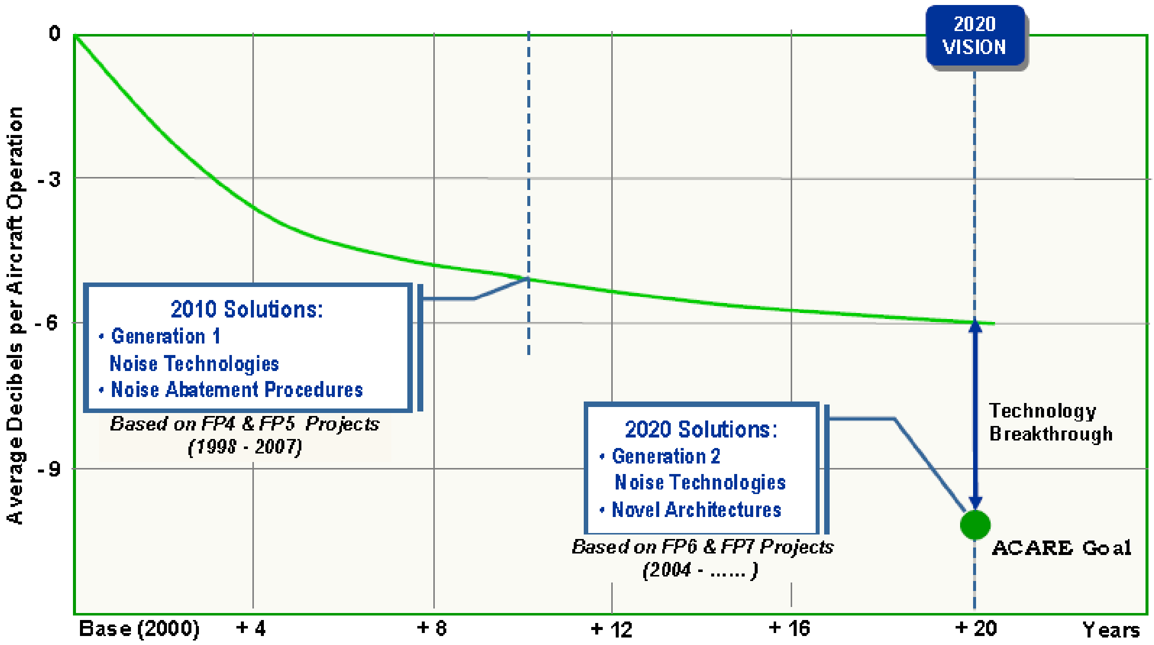
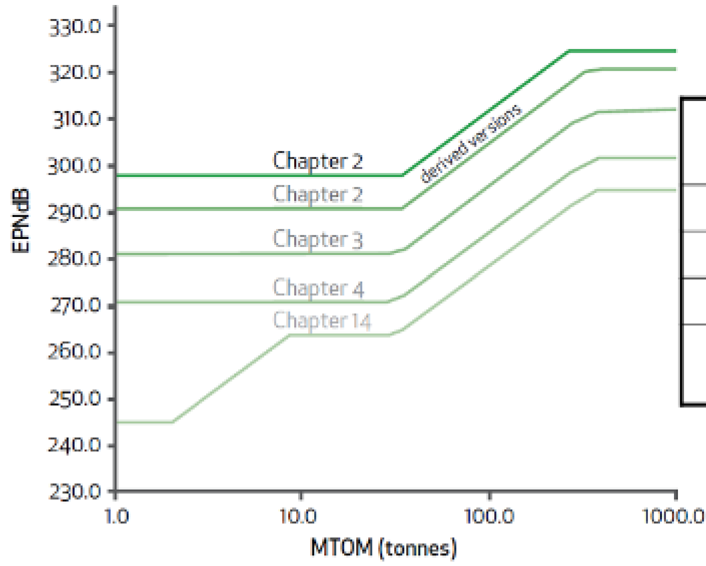


Figure 4.3 - Expected advances on noise reduction with NRT1 and NRT2, as well as the Noise Abatement Procedure

Since the year 2000 several 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 period were changed twice (Figure 4.4) – in 2006 and 2017, once again basing on NRT1 and NRT2 achievements, reached in EU (Figure 4.5). 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 Generation 1 Noise Reduction Technologies delivered to TRL6 by completed research programmes such as Silence(r) and Vital (Figure 3.26). The observed average achievement is in fact slightly over the expected 30% of the ACARE target. In dealing with the further steps towards the -10dB target (NRT Generation 2, 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.



Chapter	Applicable Year	Cum Margin (EPNdB)
2	1972	Ch. 3 ~-16
3	1978	0 (Ref)
4	2006	Ch. 3 +10
14	2017 & 2020	Ch. 3 +17 (Ch. 4 +7)

Figure 4.4. Certification requirements for aircraft noise due to ICAO standards

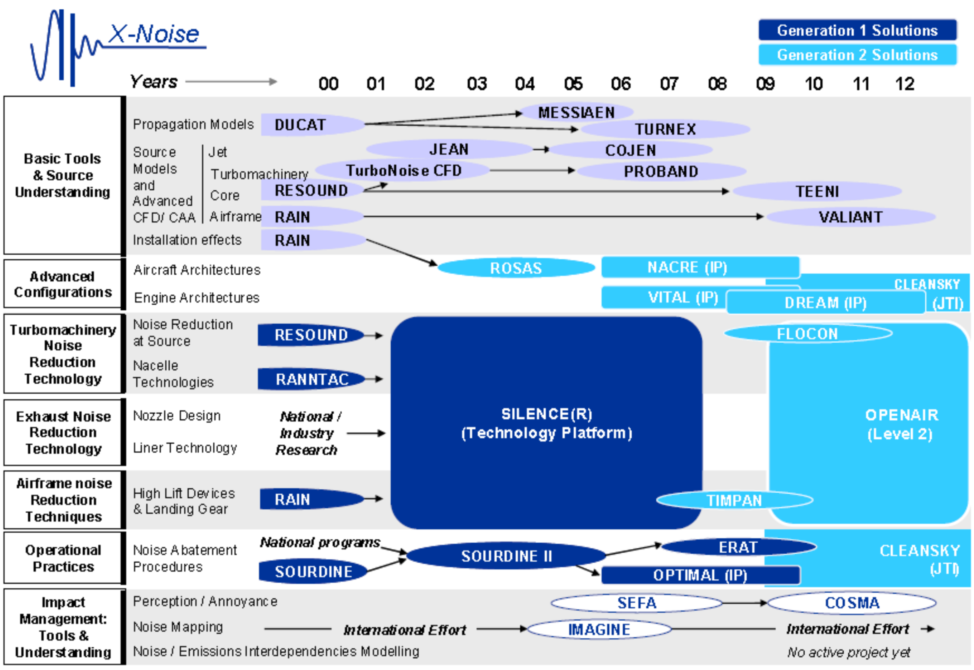


Figure 4.5. Roadmap of EU Aircraft Noise Research Projects vs Key Technical Areas (Generation 1 and 2 solutions - NRT1 and NRT2 performances – were achieved by results of the projects shown and classified in accordance with priority acoustic sources)

At the end of the OPENAIR project NRT2 have achieved TRL 4/5 (look in the Figures 4.2 and 4.6) 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.

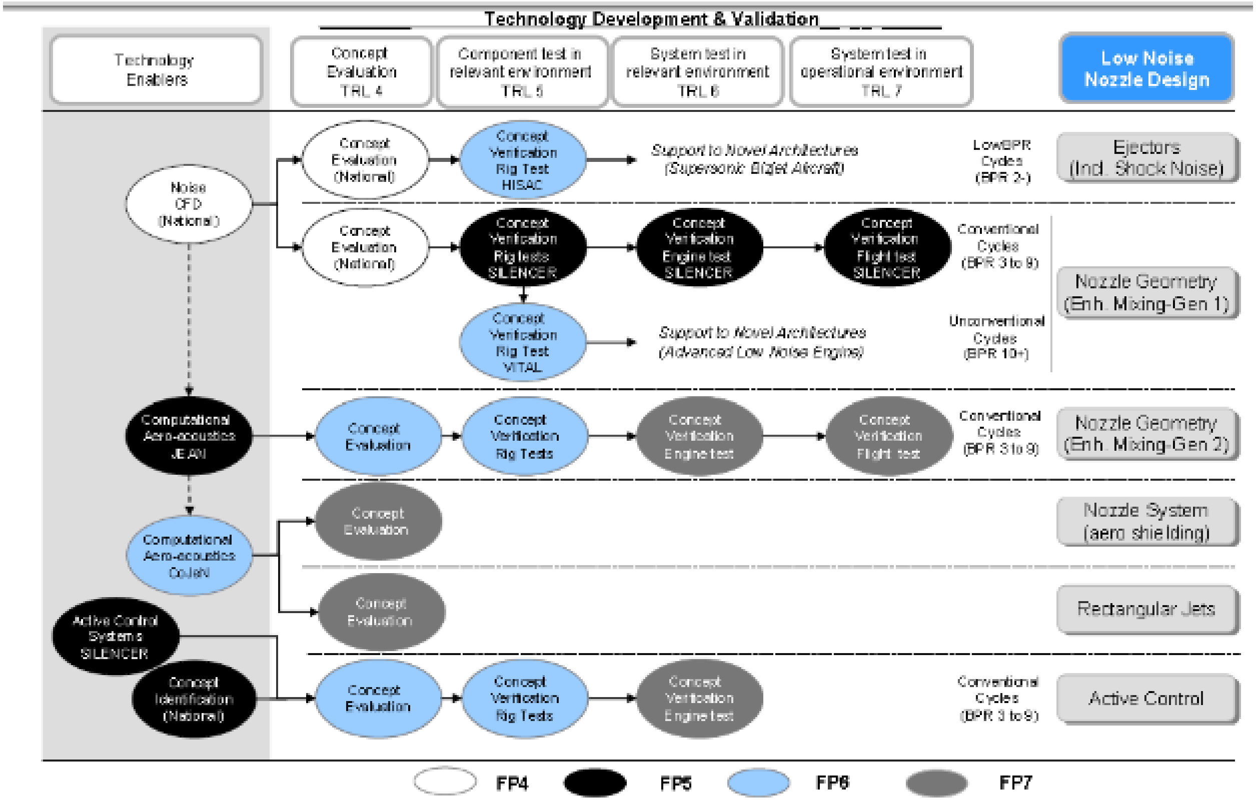


Figure 4.6 - Noise Reduction Technologies Development & Validation

When combining CLEAN SKY interim analysis (2014) 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 4.1).

While such a progress has been registered in terms of secured achievements, the gap to be covered by new programmes has basically 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.

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 4.1. Technology Readiness Level and Technology Status

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 toTRL6, 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.
- Take advantage of the sustained effort on low noise operational procedures to consolidate wider implementation capability.

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 individual element differs 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.

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 consequence, a significant research effort has been and still is dedicated to noise reduction of CROR engine concepts (Figure 4.7). At this stage, based on results from model tests in anechoic wind tunnel (TRL4), 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 represent a typical 20dB noise reduction on a cumulative basis, a spectacular achievement for the European research effort initiated in 2008. To consolidate such advances, it is important that the effort is maintained through dedicated research aimed at rotor blade aeroacoustics design, engine/airframe installation (Figure 4.8) and flow control techniques. 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.

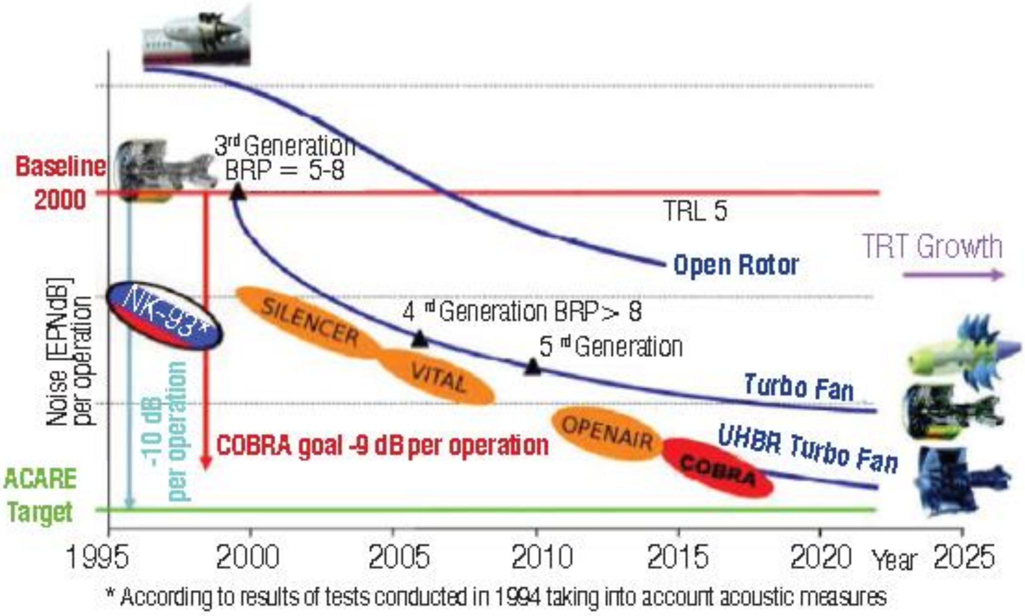


Figure 4.7 - Programme Level & EPNL reduction for aircraft noise due to technology improvements

Figure 4.8 - Airbus views on a futuristic design for 2030 - future noise reduction technologies with contribution of engine/airframe installation effects

4.1.2 Aerodynamic Noise and Operating Procedures

The progress in the reduction of engine noise implies that: (i) it still 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 noise from the extended undercarriage and its wells and other cavities, and the deflections of control and high-lift surfaces.

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.

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 4.9). 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. The IEP concluded 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 corresponding change of the aircraft structure, as described in [**Dobrzynski W. M**].

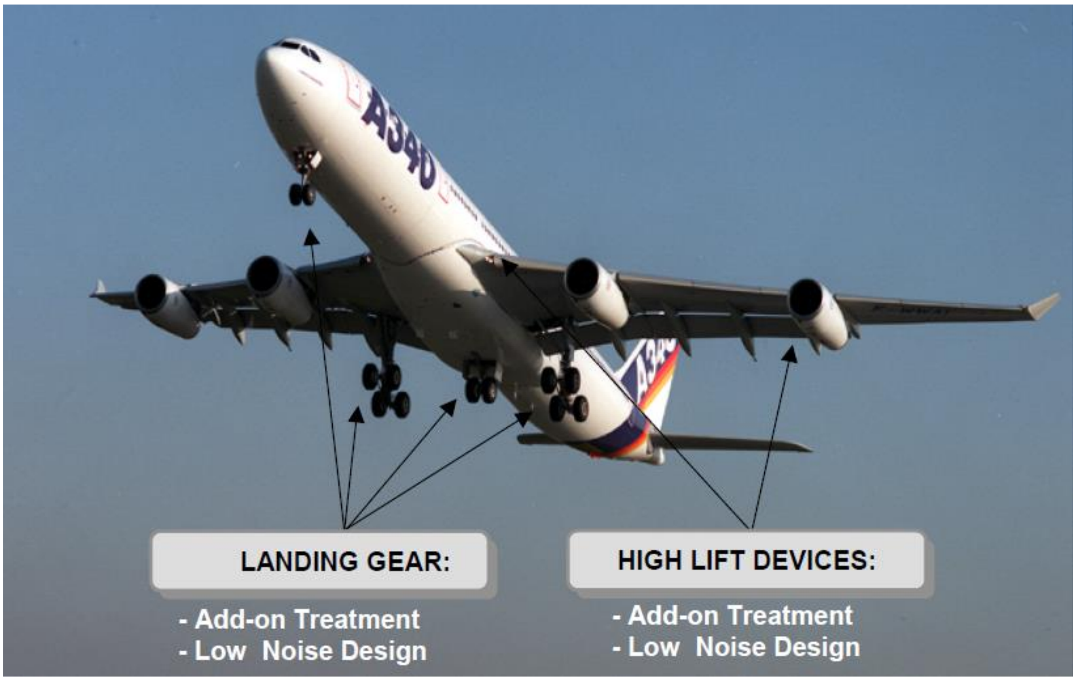


Figure 4.9 - Airframe noise reduction technologies

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.

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 4.8) 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.

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 own 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] contains a list of current NADP's in use by air carriers for a wide range of aircraft types. A number of them was assessed during EU Silence(R) project for their possible contribution to ACARE 2020 goal (Figure 4.10):

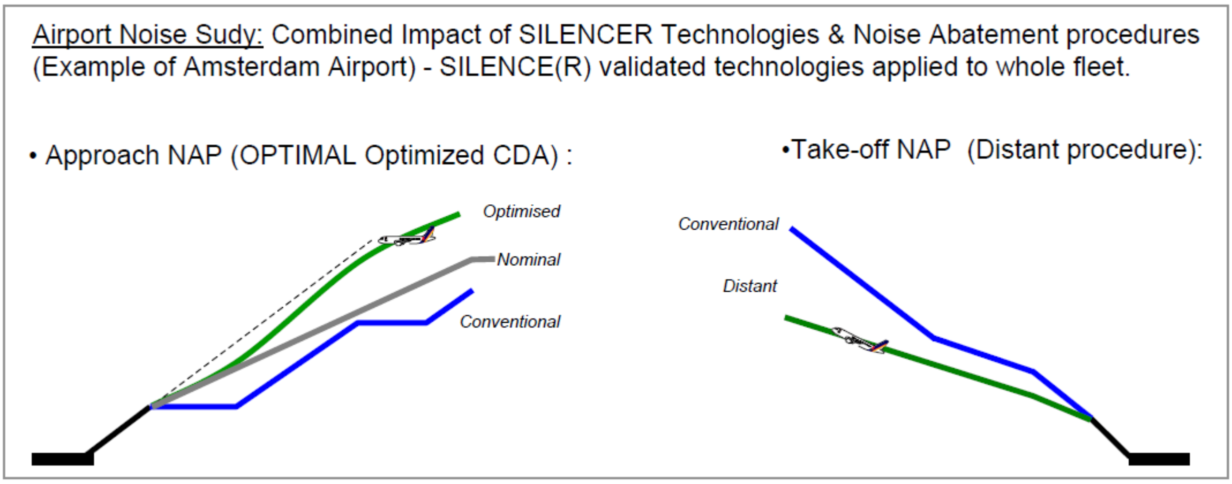


Figure 4.10. Departure and approach noise abatement procedures

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. Noise abatement operational procedures in use today can be broken down into three 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]:

— 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 fuel savings per landing; and

— 90 to 630 kg CO_2 and 60 to 440 pounds 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 in order 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) 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 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 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]:

- 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. The Figure 4.11 provides a rough survey of the most important non-acoustic variables for long-term annoyance and for annoyance at night.
- Provide the 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.

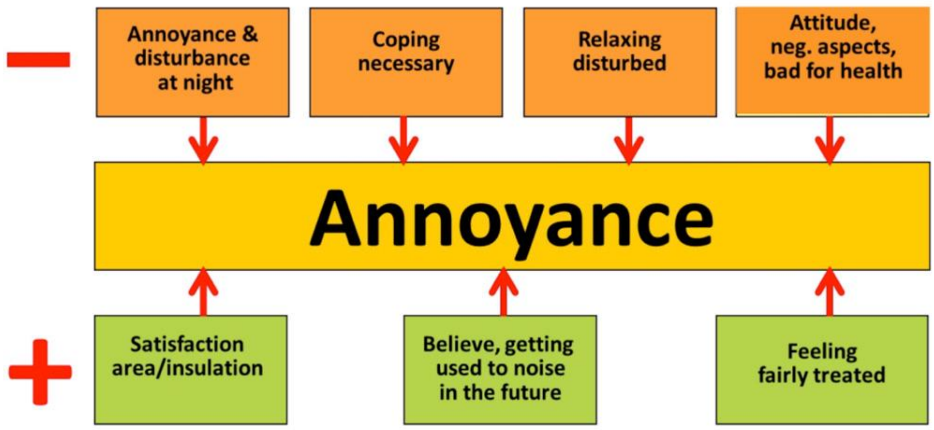


Figure 4.11. Overview of most important non-acoustic factors contributing to aircraft noise annoyance [Collin D]

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

- Improved numerical simulation capabilities, together with test facilities incorporating advanced measurement techniques, in order to support further noise reduction at 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.

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".

4.1.3 Local Emissions of CO_2 and NOx

There are growing concerns about the impact of aviation on the atmosphere with respect to 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 be 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].

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].

FORUM-AE puts 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 CO2 or non-CO2 trade-offs with noise environmental constraint, comparison between other transport modes (particles, CO2), introduction of a new aircraft CO2 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 guidance are established for criteria pollutants. However, the ambient measurement of ultrafine particle number concentrations is not yet standardized.

The Figure 4.12 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 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-Lye R]. Some of the gaps for the production of airport emission inventories are displayed in the Table 4.2:

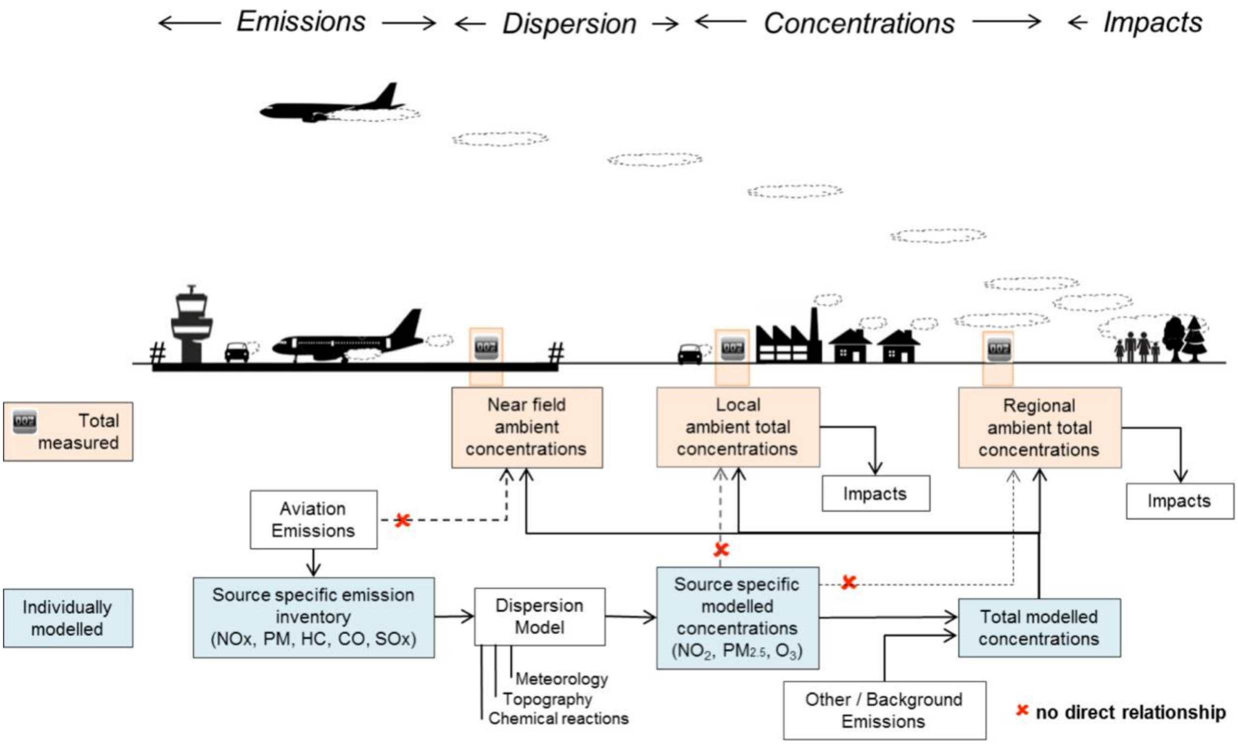


Figure 4.12 - Schematic presentation of emissions, dispersion, concentrations and impacts with their interaction at airport level [Miake-Lye R]

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

ACARE's environmental research is driven by five goals to be achieved by 2050. Among them are CO_2 emissions per passenger kilometre have been reduced by 75%, NO_x 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.

Airport emission inventory and air quality modelling improvements are required, which will ask that models more accurately predict concentrations. As illustrated in previous Table there is still a lot for improvement in airport emission inventory making and that further consolidation is needed in 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 the 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 NO_x emissions. As such, following the adoption of the original emissions standards, more stringent NO_x limits have been periodically introduced in order to mitigate the potential trade-off with market-driven fuel burn improvements. The NO_x 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 NO_x 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 turbo-jet and turbo-fan aircraft engines was first adopted by ICAO in 1981. The stringency of that Standard was successively increased at CAEP/2, 4, 6, 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 (SAQ) 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 States. Also, they provide policy makers with a view of what technology could be expected to deliver for 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 horizon.

The goals can be seen in the Figure 4.13, 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-years timescales based on the leading edge of control technologies; while standards on the other hand are based on already certified technology.

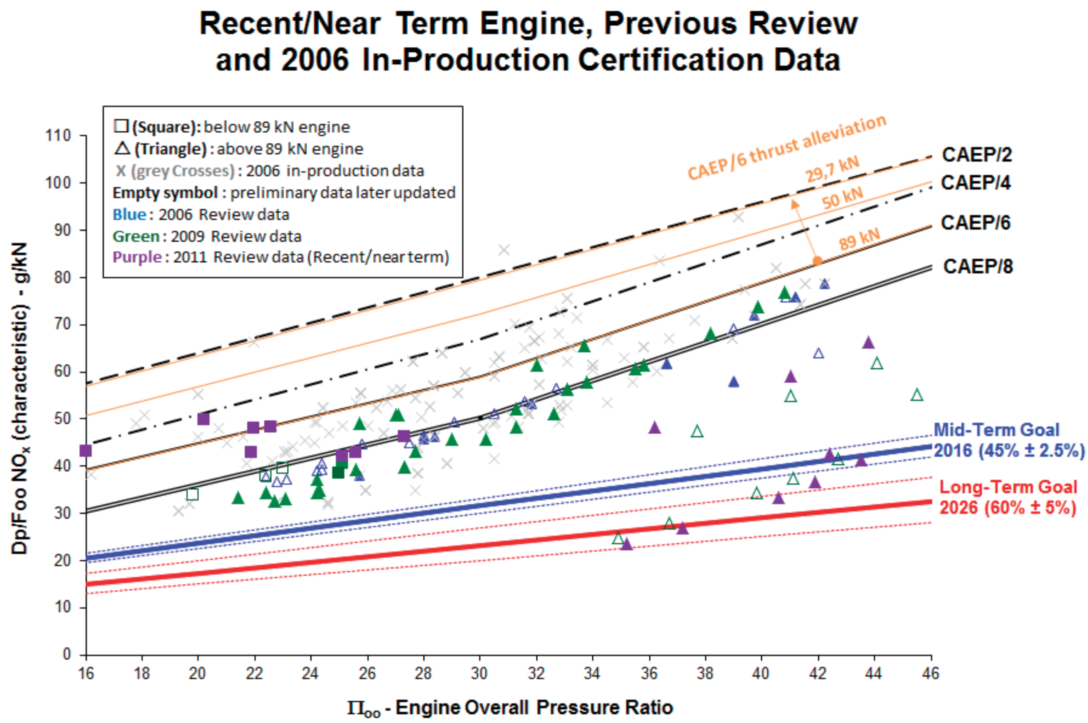


Figure 4.13. Historical ICAO certification Standards together with the 2006 MT & LT goals.

The Figure 4.13 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. The Figure 4.14 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.

The Figure 4.13 uses the recognized NO_x certification metrics and shows the amount of NO_x produced from an LTO cycle (Figure 4.15) 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 band width was greater for the longer time period. The medium term (MT) goal for 2016 was agreed at 45% ± 2.5% below CAEP/6 at OPR 30, and the long term (LT) goal for 2026 at 60% ± 5% below CAEP/6 also at OPR 30.

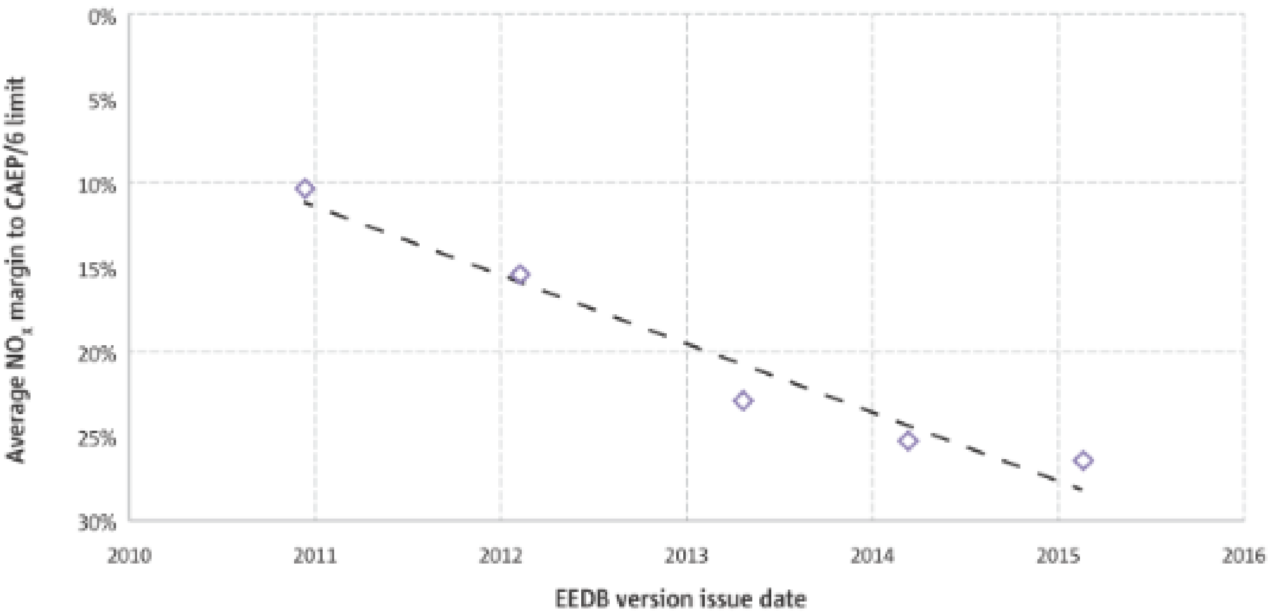


Figure 4.14. Improving average NOx margin to CAEP/6 limit for in-production engines shown in successive versions of the ICAO EEDB

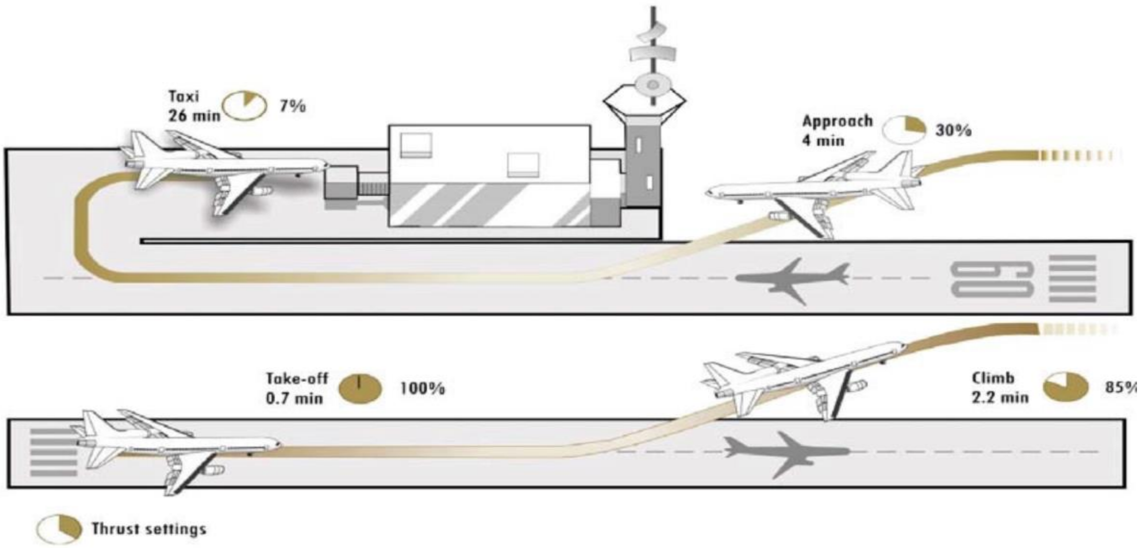


Figure 4.15. Illustration of ICAO emissions certification procedure in the LTO cycle.

The second CAEP IE review for NO_x emission 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 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) 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.

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 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 4.16 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, but 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 wide spread 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.

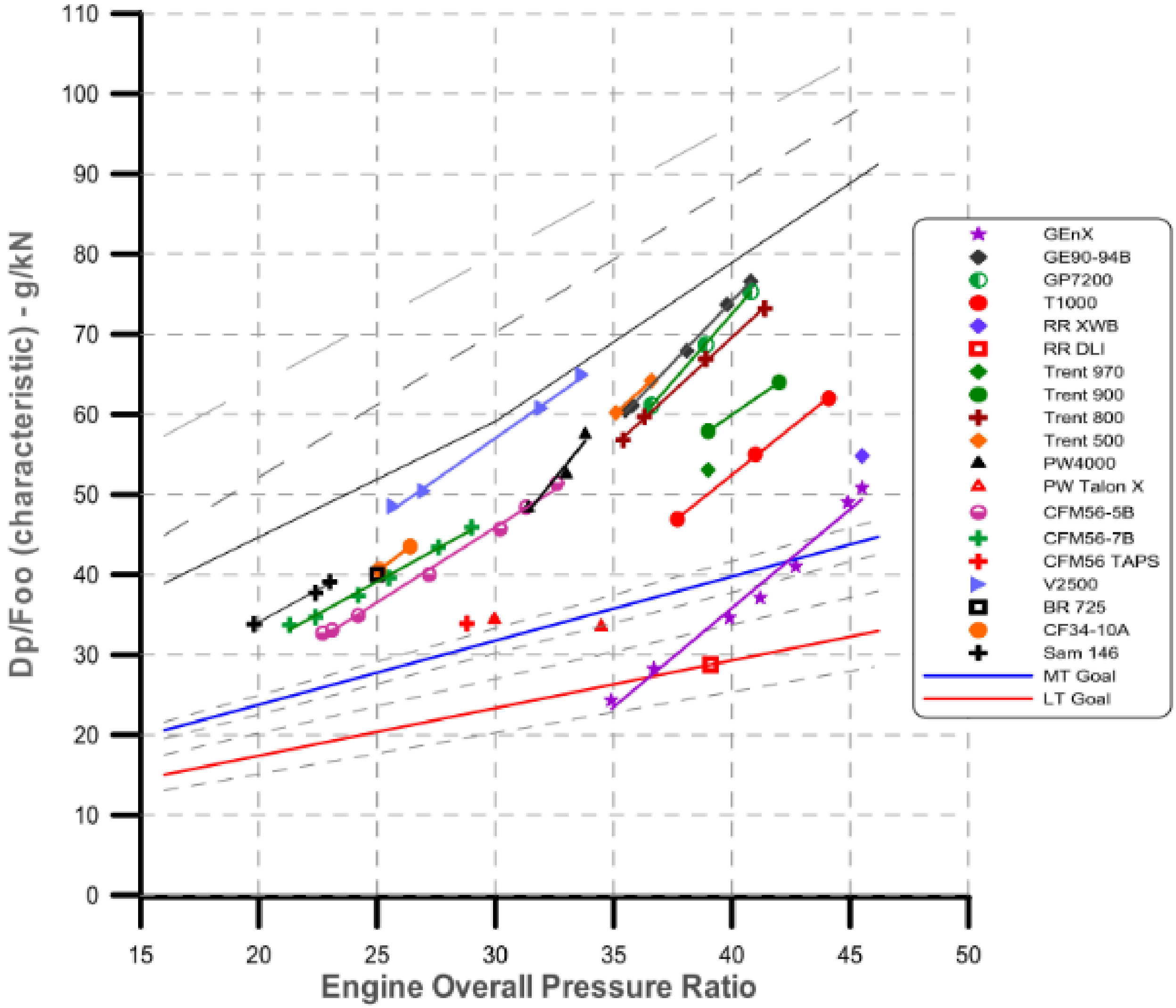


Figure 4.16. 2009 Review data with RQL combustors in grey and new mid-OPR engines. Generation staged DLI combustors in red. Note these data points area mixture of certificated engines and high TRL developments

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

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 to higher Technology Readiness Levels [ICAO CAEP/8-IP/11].

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].

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.

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 in order 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 the aim of encouraging 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 the Figure 4.17, 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 CO2 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.

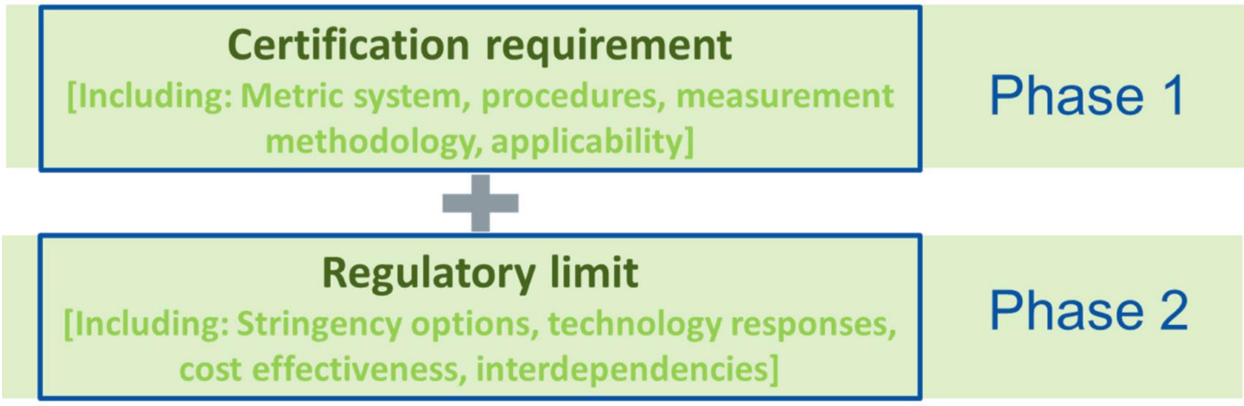


Figure 4.17 -The framework and development phases of the CO_2 Standard

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 with the aim of encouraging 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 undergo a 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). The Figure 4.18 shows an overview of the CO_2 Standard regulatory limit lines for both NT and InP CO_2 Standards. 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 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.

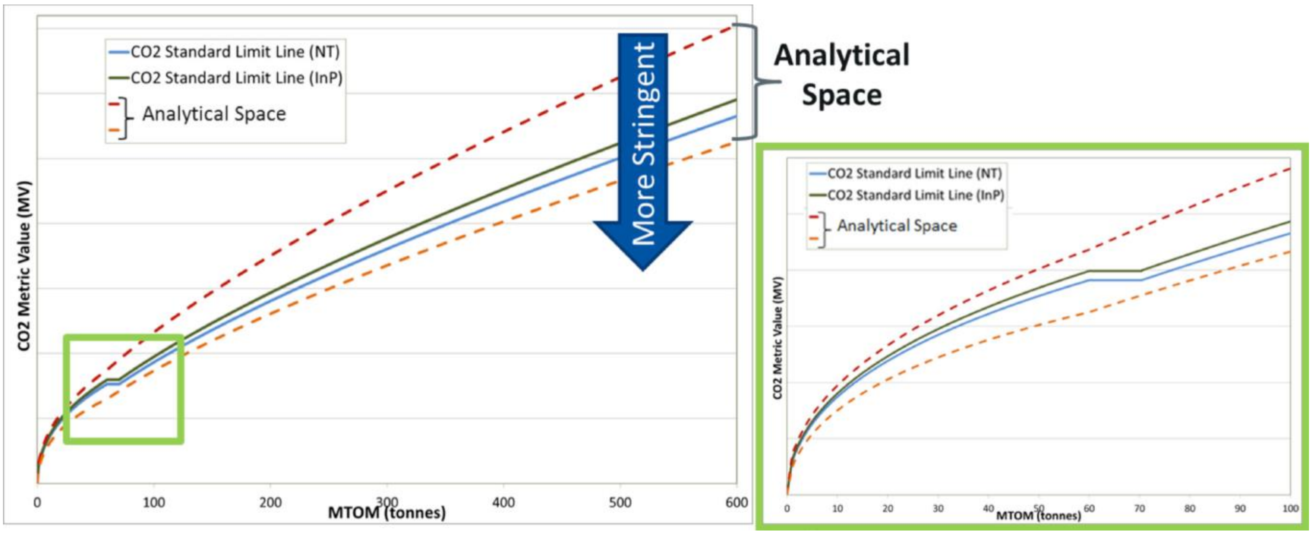


Figure 4.18 - The CO_2 Standard regulatory limits for the aircraft

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, it is clear that 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.

The Figure 4.19 presents full-flight CO_2 emissions for international aviation from 2005 to 2040, and then extrapolated to 2050. This Figure 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. 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. Although not displayed in a separate Figure, the demand uncertainty effect on the fuel burn calculations shown in Figure 4.19 has an identical effect on the CO_2 results. Based on the maximum anticipated fuel consumption in 2020 (Scenario 1) and the anticipated Scenario 9 fuel consumption in 2040, a minimum CO_2 emission gap of 523 Mt is projected in 2040. Extrapolating Scenario 9 to 2050 results in a 1,039 Mt gap.

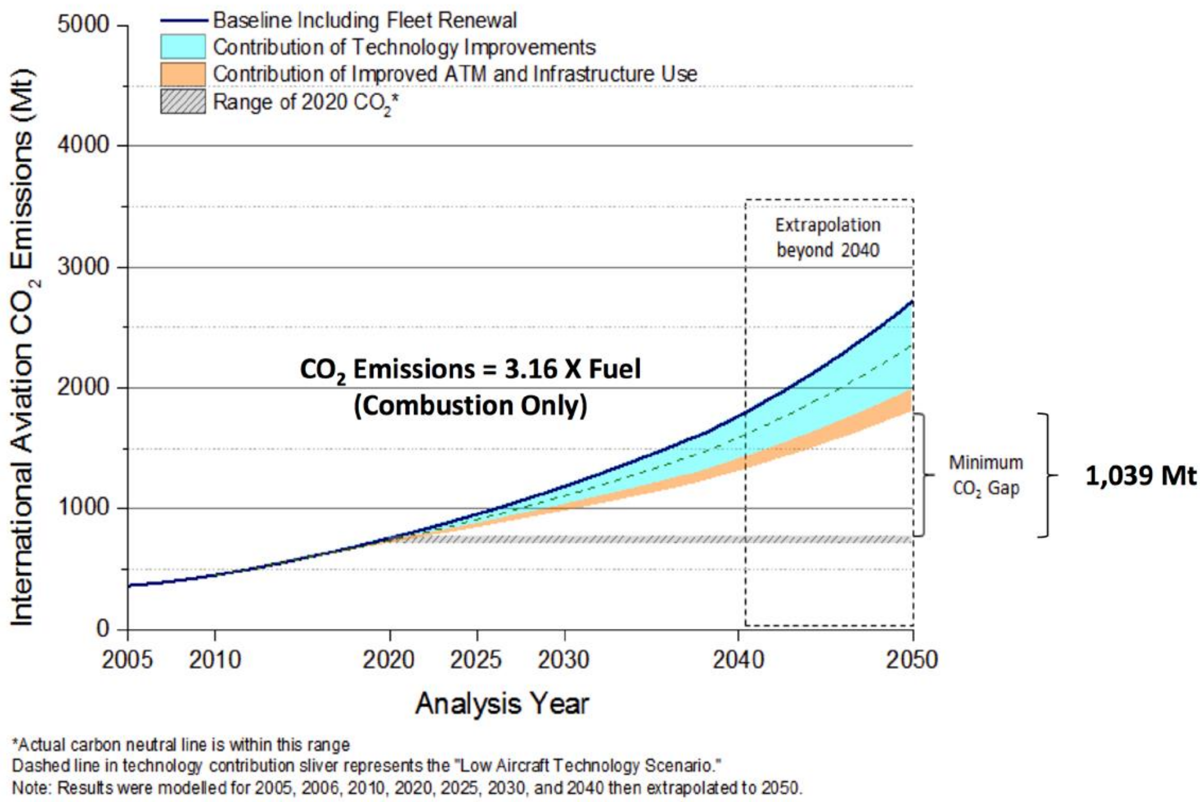


Figure 4.19 - CO2 Emissions Trends from International Aviation, 2005 to 2050

The Figure 4.20 provides results for global full-flight fuel burn for international aviation from 2005 to 2040, and then extrapolated to 2050. The fuel burn analysis considers the contribution of aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements) to reduce fuel consumption. The Figure 4.20 also illustrates the fuel burn that would be expected if ICAO's 2 per cent annual fuel efficiency aspirational goal were achieved. The trends presented in the Figures 4.19 and 4.20 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.

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.

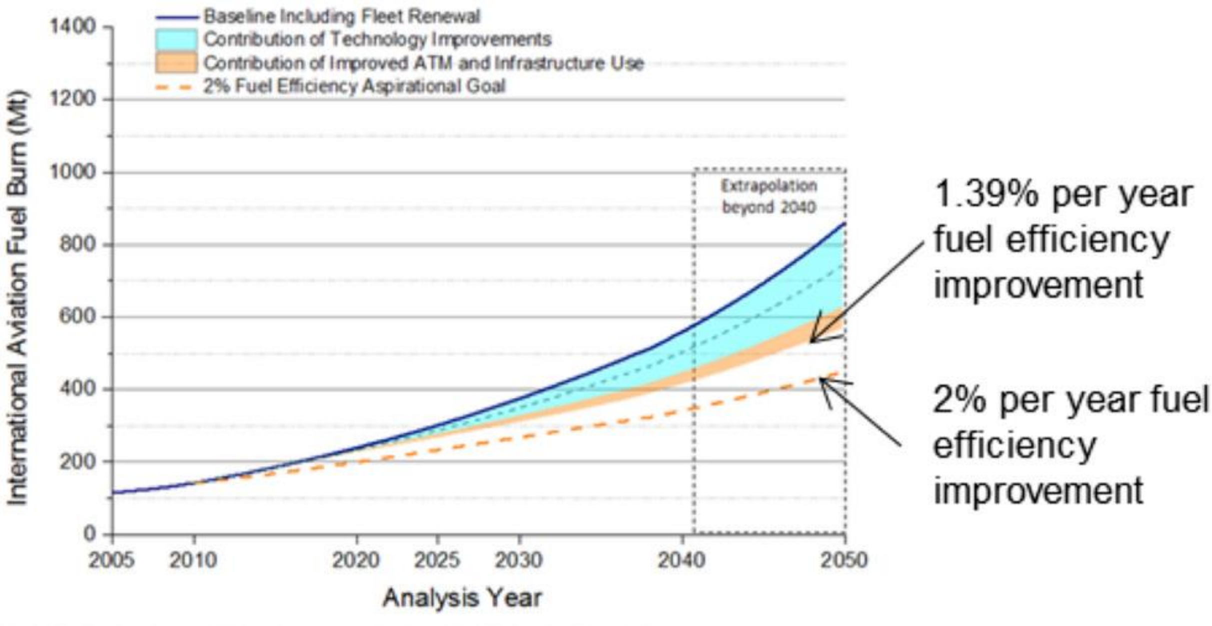


Figure 4.20. Fuel Burn Trends from International Aviation, 2005 to 2050

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.

The Figure 4.21 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.

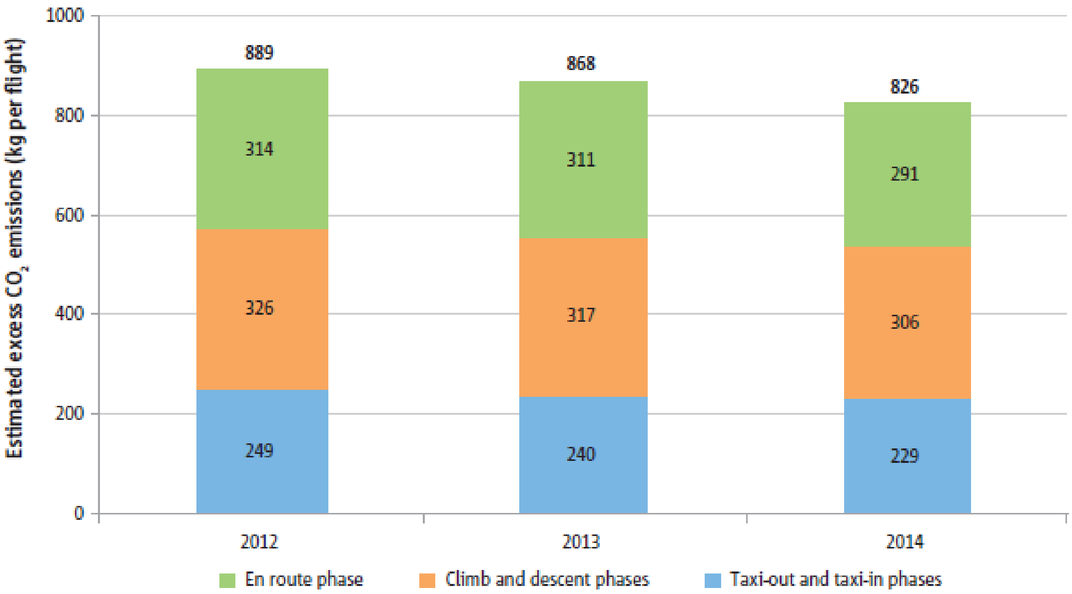


Figure 4.21. Estimated excess CO_2 emissions per flight are decreasing in taxi, take-off, climb/descent and en route phases

FORUM-AE's reference when assessing European progress towards ACARE emissions CO_2 & NOx goals is shown in the Figure 4.22. One should also note that NO_x 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 following [FORUM-AE]:

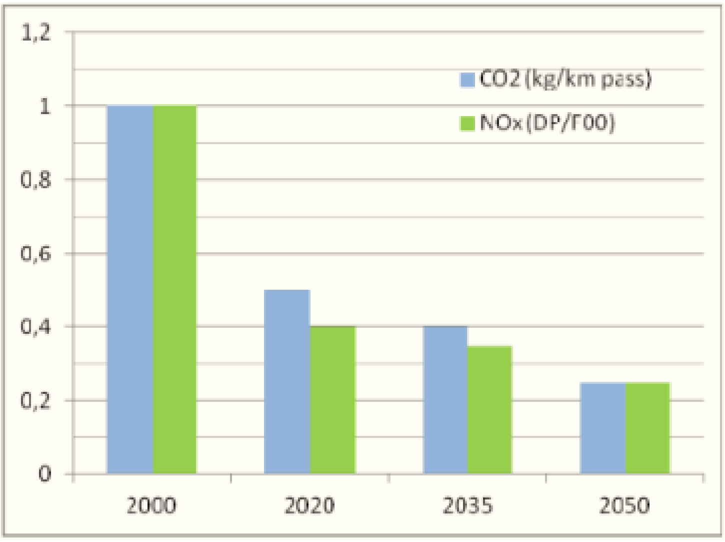


Figure 4.22. ACARE CO2 & NOx goals calendar (using CAEP6 margin for NOx) [FORUM-AE]

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, share of aviation could be above 5% in 2050.

ACARE 2050 very challenging CO2 reduction objective would permit to mitigate substantially the increase of aviation CO2, 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 in order to progress towards this ambitious goal.

Aircraft/Engine panel of technologies (an exhaustive list would be very long, and one can refer to SRIA-Vol.2 enablers table and to 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 CO2 goal.

The recommended new nvPM standard (ICAO CAEP/9 meeting in 2013) has been developed for the certification of aircraft engines emissions and is set at the engine level, in a similar way to the current ICAO engine emission standards. The recommended new nvPM standard will apply to engines manufactured from 1 January 2020 and is for the certification of aircraft engines with rated thrust greater than 26.7kN. 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.

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

- The combustor technology itself in order to ensure both NOx & nvPM ambitious low levels: enhanced lean combustion in general (achieving TRL6 maturity & extending its application to 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 absolutely 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).

4.1.4 Cruise Efficiency and Global Emissions

In 2012, aviation represented 13% of all EU transport CO2 emissions, and 3% of the total EU CO2 emissions. It was also estimated that European aviation represented 22% of global aviation's CO2 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**].

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.

Combining air traffic and environmental indicators together shows some signs of growing economic and connectivity benefits from aviation (measured in passenger kilometres flown) without a proportionate increase in environmental impact (Figure 4.23). 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 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 has 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.

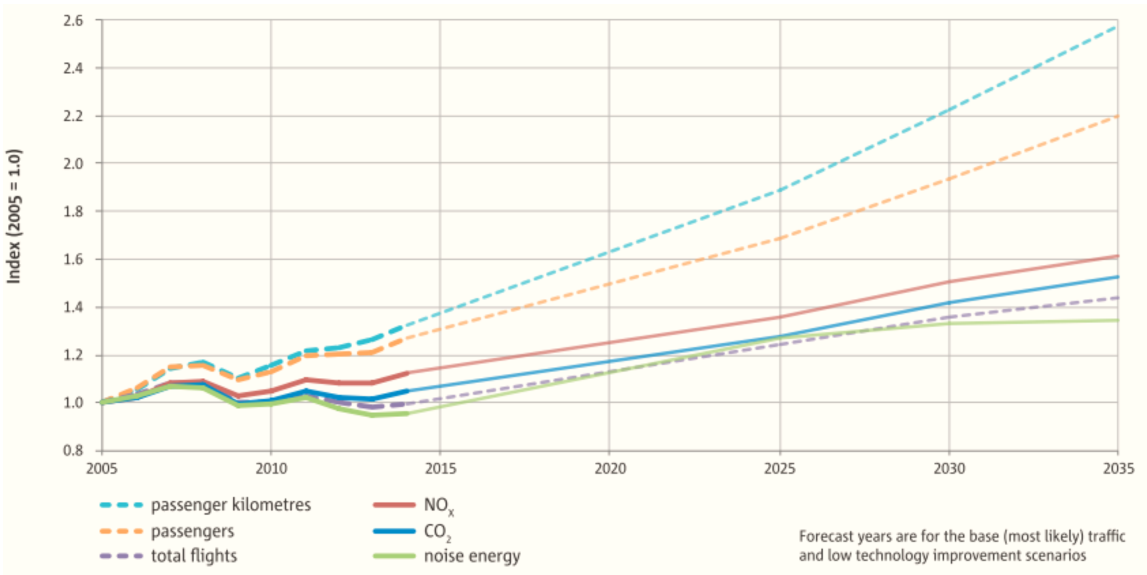


Figure 4.23 - Noise and emissions forecast to grow slower than passenger kilometres

The connections between aviation emissions and radiative forcing, climate change, and its impacts and potential damages are shown in the Figure 4.24. 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, increase 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.

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.

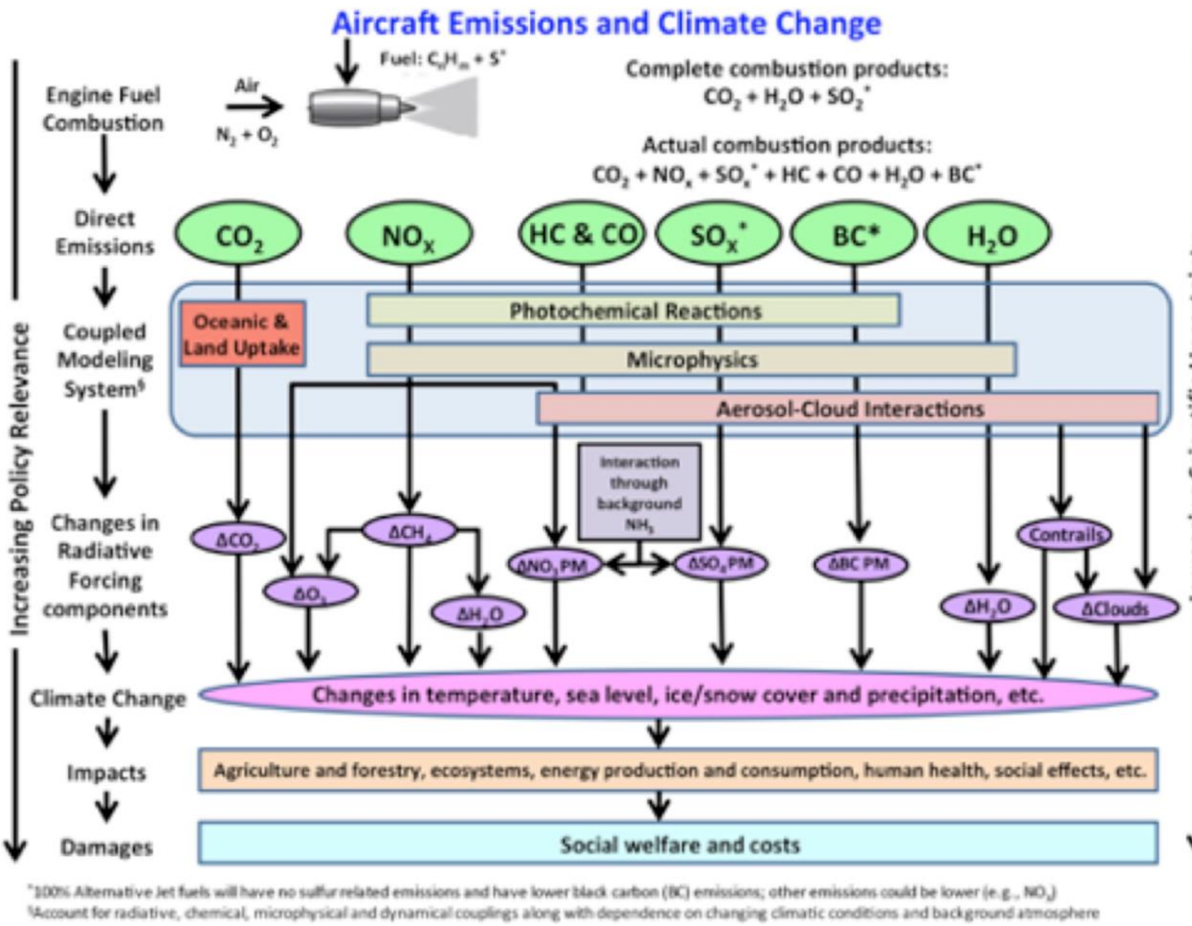


Figure 4.24 - Updated schematic of the principal emissions from aviation operations and the relationship of emissions to climate change and impacts. The terminology, ΔX, indicates a change in component X. The term, Δclouds, represents contrail induced cloudiness and aerosol-cloud interactions. (From Brasseur et al., 2015).

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 new 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.

Aircraft CO_2 emissions increased from 88 to 156 million tonnes (+77%) between 1990 and 2005 according to the data reported by EU28 and EFTA Members States to the United Nations Framework Convention on Climate Change (UNFCCC) (Figure 4.25). According to data from the IMPACT emissions model, CO_2 emissions increased by 5% between 2005 and 2014. The increase in emissions is however less than the increase in passenger kilometres flown over the same period (2005 to 2014). 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.

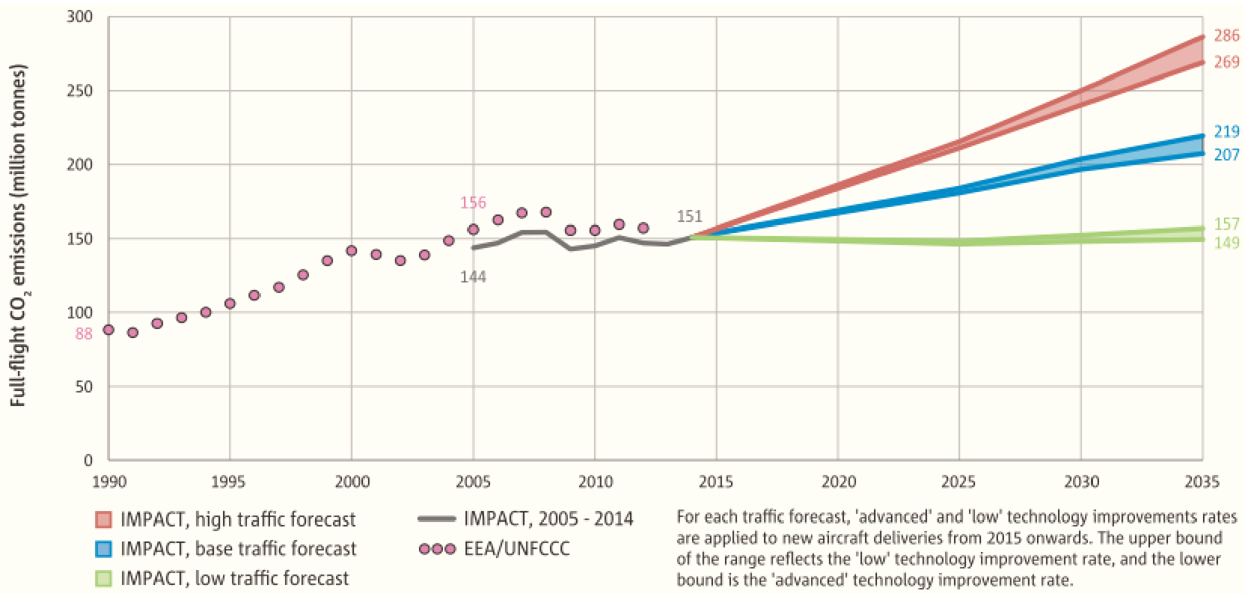


Figure 4.25 - After remaining stable between 2005 and 2014, aircraft CO2 emissions are likely to increase further

NO_X emissions have also increased significantly (Figure 4.26): +85% (316 to 585 thousand tonnes) between 1990 and 2005 according to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) data from the UN Economic Commission for Europe, and +13% between 2005 and 2014 according to IMPACT data. Under the base air traffic forecast and assuming an advanced NOX technology improvement rate, emissions would reach around 920 thousand tonnes in 2035 (+42% compared to 2005).

Current and future technological developments to achieve the challenging ACARE 2050 CO2 goal are essential to mitigate substantially the increase of aviation CO2, with realistic traffic growth assumption

(Figure 4.27). 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.

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.

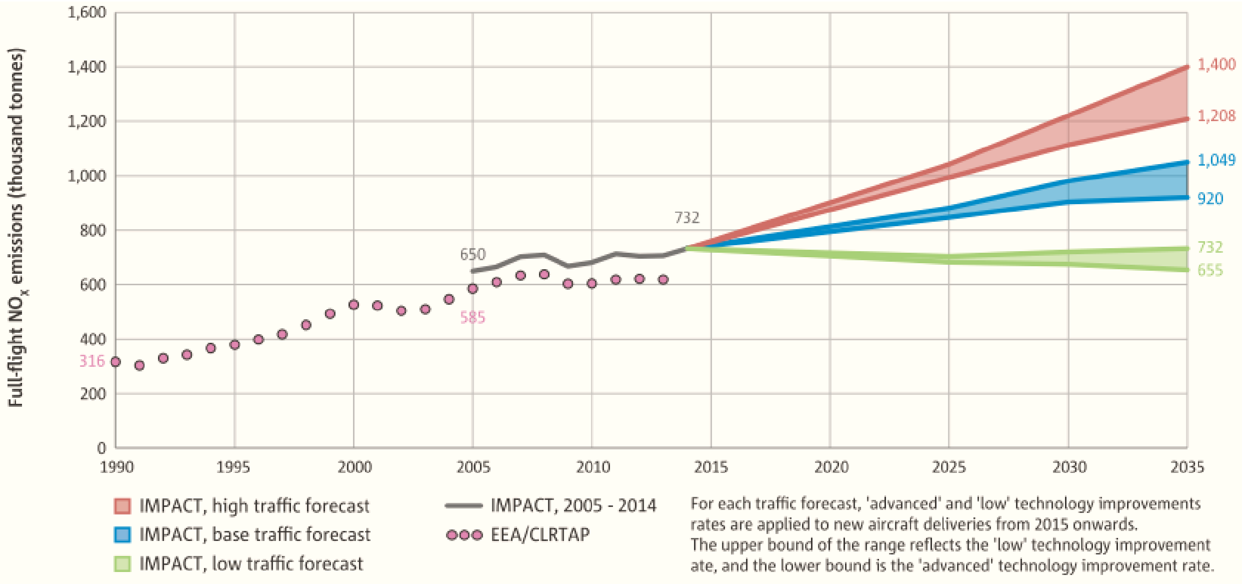


Figure 4.26 - NOX emissions are likely to increase in the future, but advanced engine combustor technology could help mitigate their growth

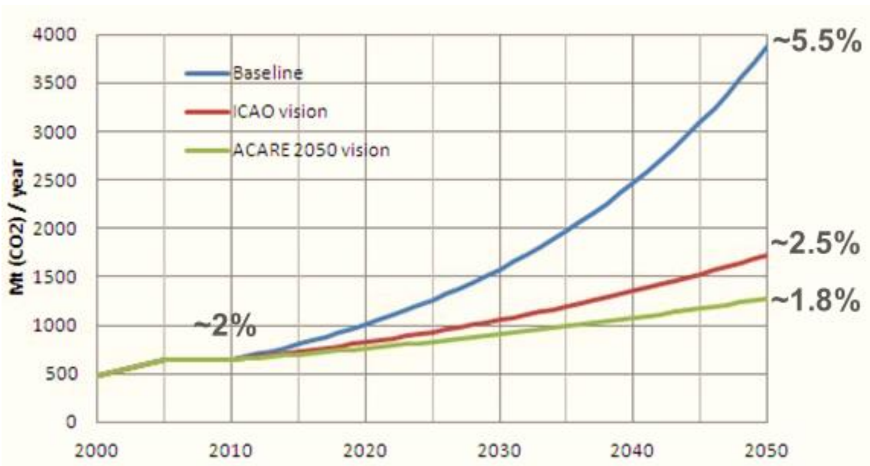


Figure 4.27 - Global aviation CO2 forecast with ACARE assumption
(Assumptions: ACARE 2050 is achieved in 2050 and fully introduced in the 2050 fleet; there is a continuous im provement of average effiency from now to 2050; ICAO 37th assembly average traffic growth of 4.6% is taken)

A new assessment was performed against ACARE CO2 and NOx goals and is summarized in the following Table 4.3. 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 4.3 - FORUM-AE assessment against ACARE emissions goals [FORUM-AE]

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]. This was done in order to provide 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 aircraft with wide span wing and engine with a slow cold exhaust, for 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 a 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 NOx 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. On the basis of 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 emissions37, 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, aviation community is putting significant efforts in promoting the use of sustainable alternative fuels that have a reduced carbon foot print 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 stabilising the emissions in a cost-effective manner 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 participation of States on a voluntary basis, 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 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 literature (Key Topic T4.2). The prospect of emissions free airport movements is related to the 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 minimise 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 in order 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 for 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 tail plane 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) ICAO's final report to CAEP/8 meeting established the goals for four classes or categories of aircraft were as follows (Table 4.4):

Aircraft Category	Margin to Chapter 4 (EPNdB)	
	Mid-Term (2018)	Long-Term (2028)
Regional Jet	13.0±4.6	20.0±5.5
Small-Med. Range Twin	21.0±4.6	23.5±5.5
Long-Range Twin	20.5±4.6	23.0±5.5
Long-Range Quad	20.0±4	23.5±5.5

Table 4.4 -The noise reduction goals for four classes or categories of aircraft (Source: ICAO)

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 Clean Sky 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, 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 gear box 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 up 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 4.28). 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.

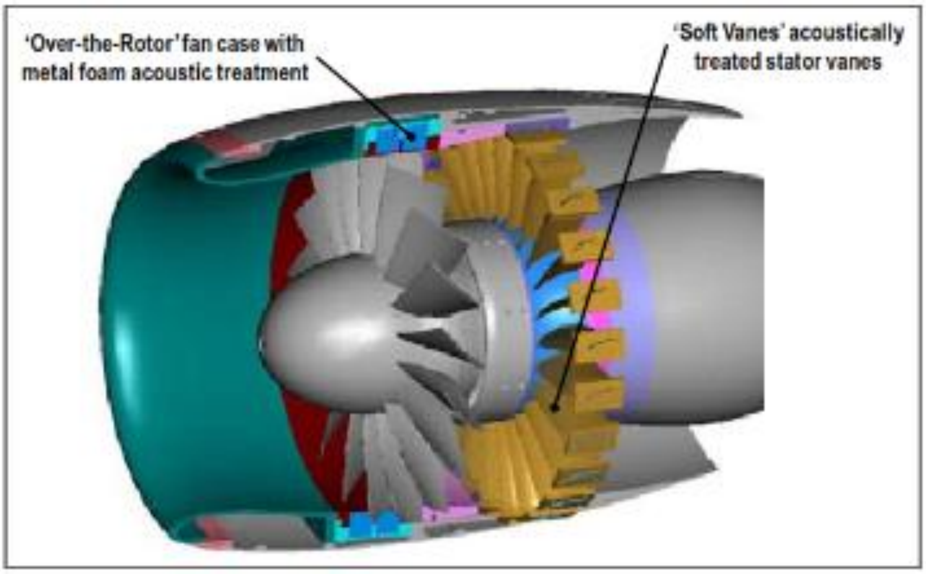


Figure 4.28 - Illustration of the UHB Fan Model identifying the locations of two noise reduction technologies used during the NASA Ultra High Bypass Fan Noise Reduction Test, which were Over-the-Rotor acoustic treatment and Soft Stator Vanes.

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 was designed to minimize 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 Chapter 14 in a few years. From a programmatic standpoint, the main framework for such integrated research is the Clean Sky 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.

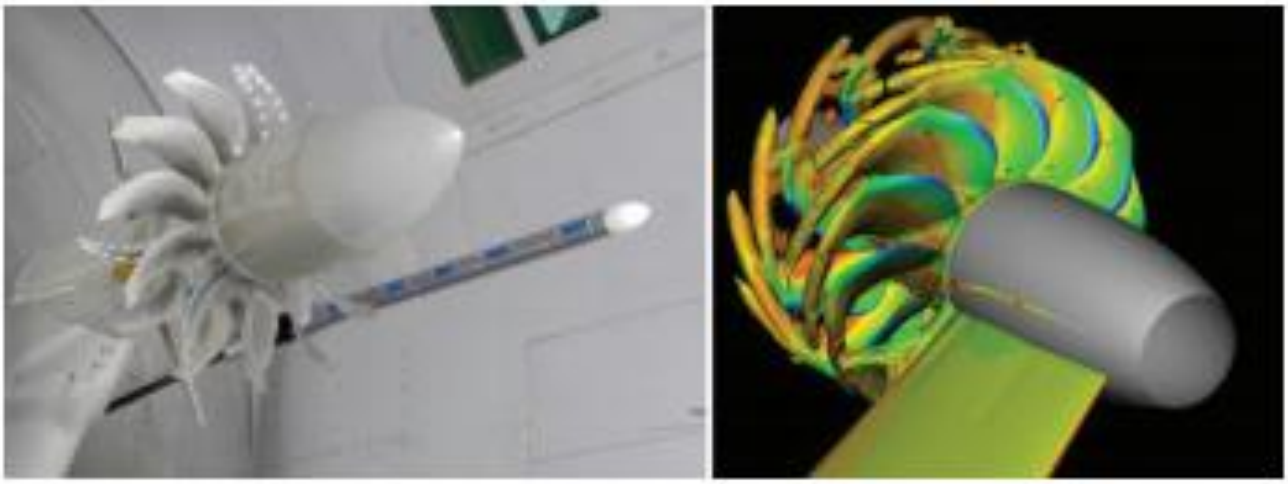


Figure 4.29 - Open Rotor mounted on Hera vehicle (Snecma) and under test at the S1 Onera wind tunnel and the simulation of interactions between the two propellers (Onera)

It is also worth mentioning that the most recent trends tend to locate these forthcoming Open Rotors (Figure 4.29) 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 as 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 4.30).

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.

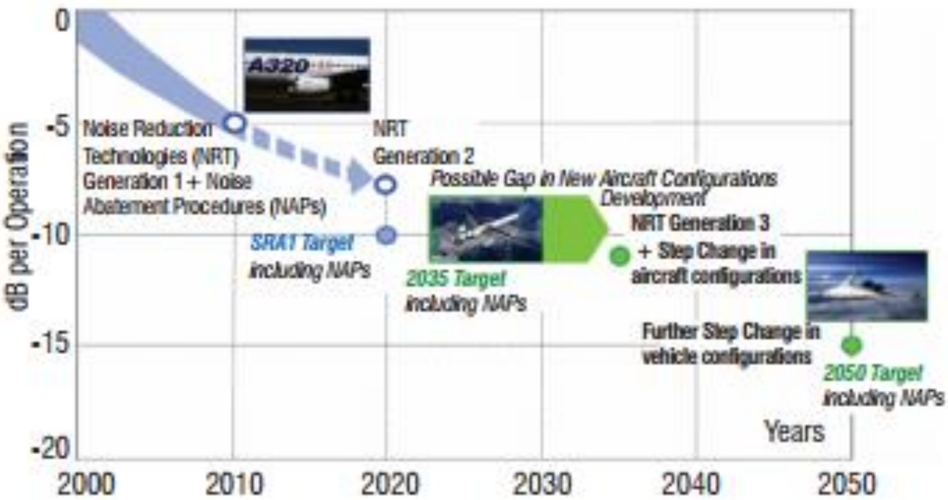


Figure 4.30 - Further ACARE objectives for 2050

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

Some of these technologies are suspected to increase the aircraft overall weight and, above all, they lead to additional drag.

Currently, few things are known about these sources, 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 UHBR, another strategy could also be to continue increasing BPR using the Open Rotor architecture (OR). 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.

KEY TOPIC T4.2– LITERATURE ON THE ASSESSMENT OF ENVIRONMENTAL TARGETS OF AVIATION

Air Pollution Related Studies

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. It is thought that doubling of aircraft movements in the next 15 years will increase the impact of aviation on global climate. For instance, Macintosh and Wallace (2009) analysed the contribution of aviation industry to climate change since 1990 and projected the international civil aviation emissions to 2025. They found that CO_2 emission of international aviation would increase more than 110% between 2005 and 2025 and so they concluded that the emissions could unlikely to be stabilized at levels consistent with risk averse climate targets without restricting demand.

Therefore, supra-national organizations on aviation put forward some challenges regarding mitigating the risks on global warming and climate change. According to Schilling (2016)'s Report the objectives set by aviation industry in 2009 cannot be met especially the long-term reduction goal of CO2 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)'s criticism regarding the challenges. Hassan et al. (2017) studied the feasibility of the aviation goals on CO2 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. According to Jovanevic and Vracarevic (2016) especially rising travel demand constrained to perform designated challenge. They studied the feasibility of global climate stabilization goals (70% reduction of CO2 emissions) with the International Civil Aviation Organization's forecasts of future commercial aviation growth and found that, air transport's emissions were going to rise five-fold (4.9 times) in the 2005-2040 period and CO2 emissions of air transport would be higher by 50% in 2040 than in 2005 due to the sudden increase in the volume of air-transport tourist trips. Moreover, they proposed that policy focus should shift to more efficient implementation of market-driven instruments, which, apart from creating incentives to develop and use low-emission technologies can also reduce the demand for travel.

Beyond travel demand, Heinemann 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 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. However, Ozaki (2017)'s study contradicted to Heinemann et al. (2017)'s study from a different perspective. He studied the potential of NO_x and proposed that if all of NO_x has been used global warming can be protected. According to Ozaki (2017) NO_x elimination should be stopped because based on his calculations for eliminating the World consumption of $2.5x10^9$ tons of NO_x 17.6 billion tons of CO_2 was released. He asserted that NO_x is playing most important role for the promotion of CO_2 assimilation and nutrient N and P in drainage should be used for fixing CO_2 and protecting global warming.

Alternative fuel usage is another option among the researchers. However, according to Noh et al. (2016) using alternative energy fuels has other research issues that should be met in future. Noh et al. (2016) 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 need to be underpinned by the awareness of the good effect of the usage of biofuel on engine process and procedure.

For mitigation alternatives, Linke et al. (2017) proposed Intermediate Stop Operations which was discussed in several scholarly works by combining it with different models. Finally, they found that a more realistic medium-range aircraft for flying ISO could on the other hand have a positive climate impact due to the expected lower cruise altitudes.

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. (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. Another social or policy perspective is coming from Gössling et al. (2016) analysed the issue and asserted that scientific insights were not translated into transport policies far reaching enough to achieve climate mitigation objectives and called this issue as an "implementation gap". In their study they analysed the issue on EU level and found that policy officers had diverging ideas of the level of decarbonisation that needed to be achieved in the transport sector and over which timelines; responsibility ownership; applied concrete measures to cut emissions. Therefore, they concluded that there were 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.

Chen et al. (2016) applied en route traffic demand model and for estimating the fuel consumption used Boeing Fuel Flow Method in their study. Based on their real-time application results, they asserted that the proposed method could characterize well the dynamics and the fluctuation of the en route emissions and provided satisfactory prediction results with appropriate uncertainty limits.

Dahlmann et al. (2016) focused in their study on preparing a methodology based on Monte Carlo simulation of an updated non-linear climate-chemistry response model AirClim. They integrated uncertainties in the climate assessment of mitigation options. After applying it to a use case they demonstrated that proposed methodology could be used to analyse even small differences between scenarios with mean flight altitude variations.

It can be asserted that all researchers in this field have a consensus on the demand of new technologies enabling ways to significantly improve aircraft performance for ACARE goals regarding emission reduction. Kling et al. (2016) discussed the issue on the modification of the inlet of an Ultra-High Bypass Ratio turbofan nacelle with adaptive structure technology with a EU funded project MorphElle which was concluded between October 2013 and November 2015. They established a pool of concepts for an adaptive nacelle inlet and performed a down selection and identified most promising one. They elaborated by using Computational Fluid Dynamics and structural simulations the selected concept and examined the impact at aircraft level. Finally, they developed a first prototype of shape adaptive mechanism as proof of concept. They found that the aircraft assessment demonstrated a possible fuel burn reduction of up to 5% for the considered mission. However, they stated that this benefit was strongly coupled with the use reference nacelle geometry which did not reflect a state-of-the-art nacelle contour.

Hayes et al. (2017) discussed the applications of exergy applications in the aviation sector by reviewing the recent literature focusing primarily on commercial applications. They derived the limitations and discussed the potential benefits for furthering proliferation of the second law method in aerospace community. They demonstrated that exergy analysis and mapping exergy destruction would provide to aerospace industry with following six items. These were;

- "A consistent common currency to allow consistent accounting across sub systems,
- Loss-producing mechanisms can be readily mapped at the system level,
- Analysis space provides physically possible/meaningful bounds,
- Provides foundation for robust and efficient optimization,
- should produce same result regardless of technique utilized, and also match the results of first law implicit methods, but providing additional insight on top of this
- an understanding of how one system influences and interacts with other non-discipline specific sub-systems" (Hayes et al., 2017)

Another perspective is coming from Balakrishnan et al. (2016) with next generation air transportation system which was presented as FAA's vision of how nation's aviation system would operate in 2025 and beyond. The NextGen initiative was established in 2003 in order to meet the challenges of predicted increase in demand. The system was including satellite-based navigation and control of aircraft, advanced digital communications, advanced infrastructure for greater information sharing, and enhanced connectivity between all components of the air transportation systems. They asserted that these characteristics of the system might have the potential to increase system efficiency by reducing delays, robustness by reducing the impact of weather disruptions and energy efficiency by reducing fuel burn. Therefore, these improvements would lead to decrease environmental impact with ensuring safety and accommodating the increased demand. For the European Counterpart Single European Sky Air Traffic Management Research (SESAR) initiative may be accepted as similar ongoing effort also.

Reynolds (2016) prepared a report for monetizing the environmental benefits of Terminal Flight Data Manager (TFDM) capabilities which reduce fuel burn and gaseous emissions, and in turn reduce climate change and air quality effects. He created a methodology for taking TFDM "engines on" taxi time savings and converts them to fuel and CO_2 emissions savings, accounting for aircraft fleet mix at each of 27 TFDM analysis reports over a 2016-2048 analysis timeframe. Finally, for all 27 TFDM analysis airports for 2016-2048, it was estimated that totally 954.000 metric tons of fuel reduction and 2.0 million tons of CO_2 reduction would be reached.

Galssock et al. (2017) analysed two case studies for highlighting the positive advantages of hybrid electric propulsion for aircraft. However, they asserted that negative compromise of electric propulsion remained significant because of the increased system weight compared to pure internal combustion alternatives. They proposed the use of Hybrid Electric Propulsion systems for transition to fully electric aircraft first and stressed that because there were hybrid and electric aircraft concepts emerging from small light sport types through to intercontinental heavy transport regulatory and certification systems should be reformed.

Karcher (2016) prepared a theoretical model for predicting properties of water droplets and ice particles in jet contrails and found that avoiding contrail cirrus formation would mitigate aviation climate impact and changing contrail formation stage had large but unexplored mitigation potential. For future developments he proposed that the atmospheric response to reductions in initial contrail ice number should be explored using global climate models with an interactive parameterization scheme for contrail ice formation depending on variable soot particle number emissions and atmospheric conditions.

Owen et al. (2010) presented new aviation emission scenarios to 2050 that were designed to interpret the IPCC SRES storylines under the four main families A1B, A2, B1, and B2 with a further look to 2100. Moreover, they calculated an additional scenario assuming that the technology targets of ACARE were achieved or not. They found that emissions of CO_2 from aviation between 2000 and 2050 were projected to grow by between a factor of 2.0 and 3.6 depending on the applied scenario and emissions of NO_x from aviation over the same period were projected to grow by between a factor of 1.2 and 2.7. Furthermore, based on their findings, they asserted that B1-ACARE scenario would differ from the SRES scenarios as it would require significant continuing improvements in fuel efficiency and some radical technological advances in the second half of the century probable.

Noise-Reduction Related Studies

Bernardo et al. (2016) studied on noise reduction by considering fleet-level analysis. They used rapid automated airport noise models which can be simulated by using Design of Experiments. They used surrogate models to model the airport noise space in conjunction with the equivalency assumption to examine two potential technology scenarios in a target forecast year, simulating technology and market performance factors to identify vehicle classes that could have the greatest impact in reducing contour area. Based on their findings, they 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 contour area.

Schwaiger and Wills (2016) proposed that cyclo-gyro propulsion can be used for vertical launch and had potential to achieve efficiency beyond the range of conventional fixed wing and rotorcraft. They assumed that their technology was feasible for VTOL aircraft that can safely form densely packed swarms and would solve the challenges facing the air environment of the future.

Postorino and Mantecchini (2016) analysed the effectiveness of airport noise mitigation strategies and considered airport-related factors, flying paths, and aircraft type in their study. They tested their assessment process on a real case in Italy and found that their assessment model provided a priori evaluation measures that are in line with current data concerning the implemented post-variant scenario. With their approach they considered simultaneously a number of standard measures together and by the way several potential scenarios could be compared.

Bartlett (2016) aimed to determine whether current turbofan noise reduction nozzles could reduce the amount of noise for turbojet engines at two different thrust levels. He tested experimentally three turbofan engine nozzles by comparing the original turbo jet engine. He recorded six samples of thirty decibel levels and frequencies at idle and at a higher thrust level. Finally, he found that the turbofan nozzle designs used in this research project did not make any major improvements in reducing the overall noise. He determined some reductions in DB levels for some specific frequencies. Moreover, he identified that engine cycle efficiencies were degraded by these nozzles as compared to the original and proposed that alternate designs that did not penetrate the gas path could reduce the negative effects on engine parameters.

There are many studies regarding noise and aviation in literature. Therefore, for understanding the noise problem in aviation, scientometric approach is applied. Data is retrieved from Web of Science database by using "aviation" and "noise" keywords in Topic Sentence field. After search, 461 publications are reached, and metadata of these publications downloaded in text format. Then, pre-processing is applied as duplication check. Citespace open-source software is used for visualization (Chen, 2006). The timeline view of the intersection of noise and aviation field is demonstrated in the Figure 4.31:

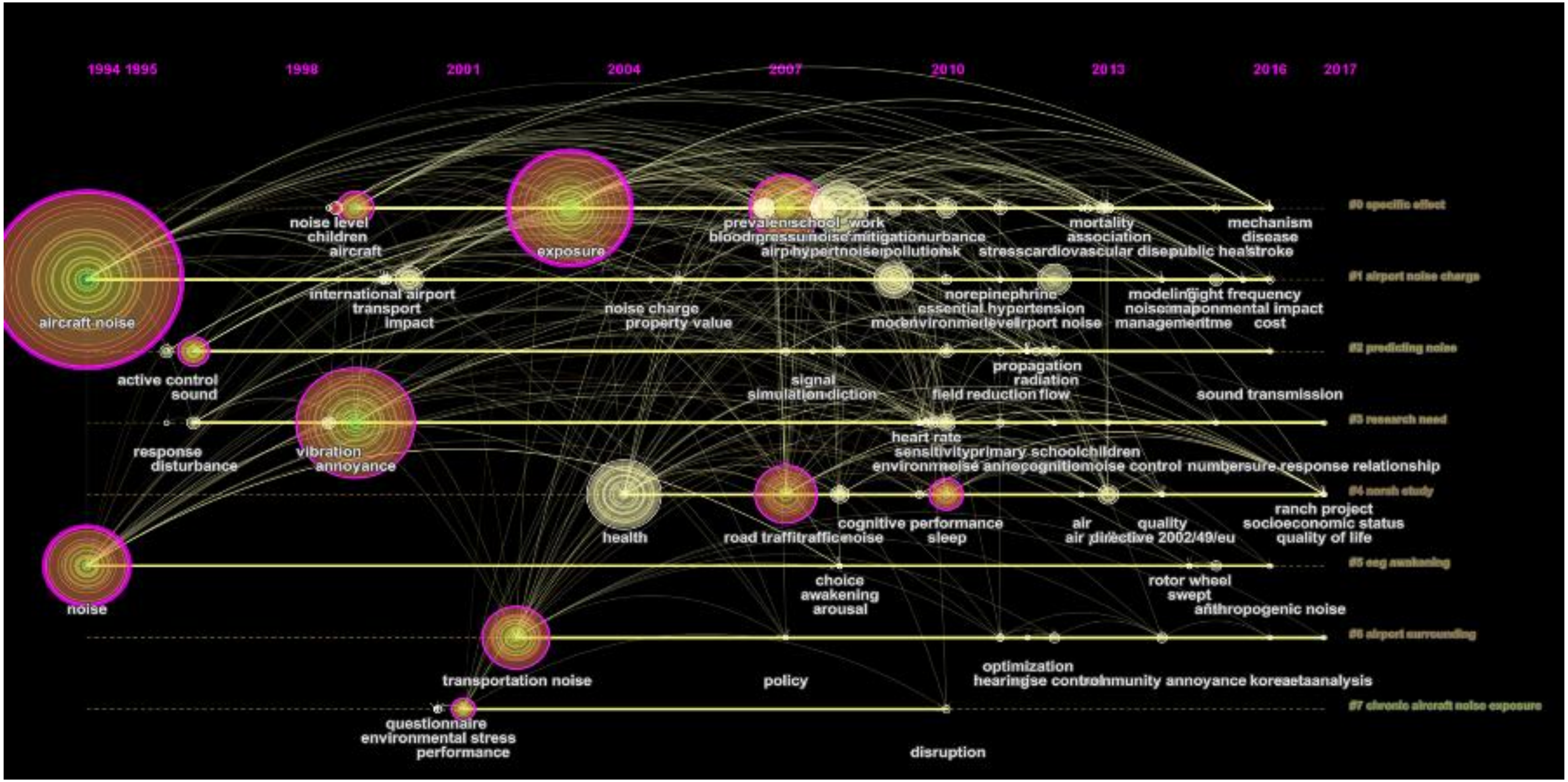


Figure 4.31 - Timeline Demonstration of Noise Related Scholarly Publication

As can be seen in figure 4.31 studies initiated since 1994 and there are 8 clusters. All clusters are represented by the yellow lines and size of nodes is representing the volume of the studies and different colours in these nodes are representing the time interval that concept studied. It can be seen that health and social issues regarding noise are mostly studied in the literature. Actually, it is assumed to find out a technology cluster in this graph but as can be seen in the fig. 1, technology related nodes are not revealed as expected. It is thought that selected keywords may affect this result.

4.2 Emissions Free Taxying at Airports

Flightpath 2050 goal 10: "Aircraft movements are emissions free when taxing".

The taxying 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. The most obvious way to achieve goal 10 is to use electric towing vehicles. There are technical aspects like ensuring compatibility of towing brackets and enough 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 taxying at airports: worldwide and at specific airport;
- Availability of vehicles, infrastructure and other costs.

The feasibility and economic of emissions - free taxiing thus critically depends on the available battery technology (Key Topic T4.2).

KEY TOPIC T4.3 – AIRCRAFT TOWING BY ELECTRIC VEHICLES

Benchmark / State of the Art-Battery

The currently preferred battery technology for ground movements at the airport or on the airfield and in the aircraft, itself are the lead-acid and the nickel cadmium battery.

Aircraft:

a. Internal engine starter generator (ESG) set;
b. 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 movement 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 4.5 – 4.8 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 4.5 - Comparison of different types of battery chemistries [adapted from Gianfranco Pistoia, "Batteries for Portable Devices", Elsevier 2005]

- <u>Aircraft- Batteries</u>

	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 4.6 - 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

	Li-ion*	Ni-Cd**
Typical battery cost / US $	~21.000	~6.500
Battery Cost per 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 4.7 - 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]

- Automotive Batteries (towing tractor, etc.…)

	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. 40 C pulse	215	3.7	-20 to 60
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 4.8 - 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]

➢ Off-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]

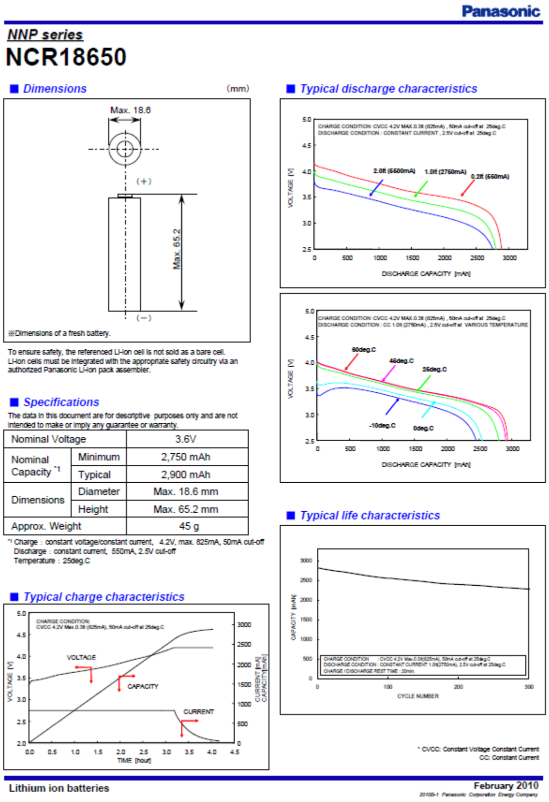
Reference State in 2010 - Battery

Since the lead acid batteries and the nickel-cadmium batteries are technically exhausted (Table 4.9), 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 4.9 - 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 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 4.32), the Panasonic NRC18650 should serve with an energy density of about 230 Wh/kg.


Panasonic

NNP series

NCR18650

■ *Dimensions* (mm)

※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 4.32 – Specification sheet for the Panasonic NRC 18650

Due to the wide range of applications, different requirement profiles result and thus many types of cells with different specifications results. Improvements are achieved with consistent chemistry mainly through improvements in manufacturing and engineering. The Table 4.10 shows an overview of various cells launched since 2010.

Cell type	Manufacturer	Nominal voltage	Capacity	Weight	Temp. Range	Specific energy	Energy density	Specific power	Cycle life	Comments
		V	Ah	g	°C	Wh/kg	Wh/L	W/kg	cycles	
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

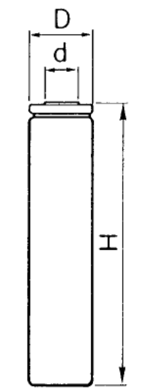
Li NMC	Molicell *IHR18650BN*	3.6	2.2	45	-20 to 60	170	450	~700	>700	Cycle life is to 80% BOL capacity at 4 A and 23°C
$LiCoO_2$ and graphite	Panasonic *NCR18650*	3.6	2.25	45		180	~500	~1400	400	High power cell, cycle life I to 80% BOL
$LiCoO_2$ and NMC and graphitic	Molicell *ICR18650M*	3.7	2.8	50	-30 to 60	216	609	~300	>300	Capacity>90% of BOL after 300 cycles at 23°C
New Nickel Platform with heat resistant	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 *NexelionWH1*	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 4.10 - Some characteristics of commercially available secondary lithium-ion cell, ordered by specific energy [Underwater Technology, 33, 3, 2016]

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 4.33) in which the energy density could be increased from 230 Wh/kg in ~2010 to 243 Wh/kg within the last years.

Cell Type NCR18650B



Dimensions(Typ.) of Bare Cell	H	64.93mm
	D	18.2mm
	d	7.9mm

Discharged State after Assembling

Specifications

Rated Capacity (at 20℃)		Min.3200mAh
Nominal Capacity (at 25℃)		Min.3250mAh
		Typ.3350mAh
Nominal Voltage		3.6V
Charging Method		Constant Current -Constant Voltage
Charging Voltage		4.2V
Charging Current		Std.1625mA
Charging Time		4.0hrs.
Ambient Temperature	Charge	+10～+45℃
	Discharge	-20～+60℃
	Storage	-20～+50℃
Weight (Max.)		47.5g
Dimensions (Max.) Maximum size without tube	(D)	18.25mm
	(H)	65.10mm
Volumetric Energy Density		676Wh/l
Gravimetric Energy Density		243Wh/kg

Figure 4.33 – Specification of the Panasonic NRC1865 battery

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.

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 electro mobility. 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 small unmanned aerial vehicle (UAV) a high energy density of the battery is very important for traveling long distances. Therefore, one can´t give a solution that meets all requirements. Rather, it requires a tailor-made solution for the different purposes. However, in the following some information on the necessary developments regarding (state of the art) lithium-ion batteries.

There are several deficiencies of actual 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. 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 lower cost to fulfil the needs of greenhouse gas reductions through 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.]*

A 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.

In addition, 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]*.

The Table 4.11 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 metal foils 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 4.11 - 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 arise 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; in addition, 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 is the 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 metal–oxygen 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.

4.3 Design and Manufacture Bearing in Mind Recycling

Flightpath 2050 goal 11: "Air vehicles are designed and manufactured to be recyclable

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).

An illuminating example of the experience and challenges of recycling is given by batteries (Key Topic T4.3).

KEY TOPIC T4.4 – BATTERIES FOR 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 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 reliable and be certifiable safe;
- To be lightweight;
- To have a consistent power output over their operating environment;
- To have a reasonable long life.

A small size, high energy density battery (Table 4.12) 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]

2) Types of aircraft batteries:

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 4.12 - Comparison of different cell chemistries used in aeronautics1

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 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 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 4.13) towards Li-ion batteries with its tremendous opportunities to be employed in *MEA*.

Li-ion cells comprise a 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. Nano-materials 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.

[1] M.Tariq, A.I.Maswood, C. J. Gajanayake, A.K.Gupta, IET Electr. Syst. Transp., 2017, Vol. 7 Iss.2, pp 93-103

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*.

Most new batteries face the same adoption curve, starting with initial resistance and then acceptance.

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.		
Changhong Battery (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 Jet Ranger helicopter	17-46
Acme Aerospace (US)	Ni-Cd	APU, Avionics, Environmental systems	B-777	47

Table 4.13 - Details of batteries used in different aircraft

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 to 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 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 *Sumitomo Metal*). 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 technical defect) required for secondary batteries, Li-ion batteries are associated with specific potential hazards which need to be taken into special consideration with regard to 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.

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[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

- 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. Consequently, the US-*Federal Aviation Agency FAA* has mandated to install a casing for the battery to contain/extinguish the fire (Figure 4.35):

Figure 4.34 - Boeing-787 relaunched the Li-ion battery system with the new design, adding an extra weight of 68kg to the weight of the airplane.

- 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.

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 may be 7 to 11 times higher than the energy stored electrically. The produced heat accelerates the reaction, resulting in a critical overheating of the battery.

In addition, it is possible that cathode materials disintegrate at high temperatures. This reaction also produces heat (exothermic reaction) and releases bound oxygen; when 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]

[5] Airbus, 18th Flight safety conference Berlin, 19-22 March 2012

Figure 4.35 – Use of batteries in a typical aircraft.

There are a number of potential threats that can be associated with aircraft batteries (Figure 4.35), their distribution networks and their charging and monitoring systems:

- 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, following preventive measures should be undertaken:

- Containment of thermal effect;
- High standard electronic protection against overheat (overcurrent, overvoltage, short circuits);
- Specific choice of battery structural material and design;
- Battery management system with 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.

[6] https://www.skybrary.aero/index.php/Aircraft_Batteries

5.2) Li-ion batteries in the cabin[7]

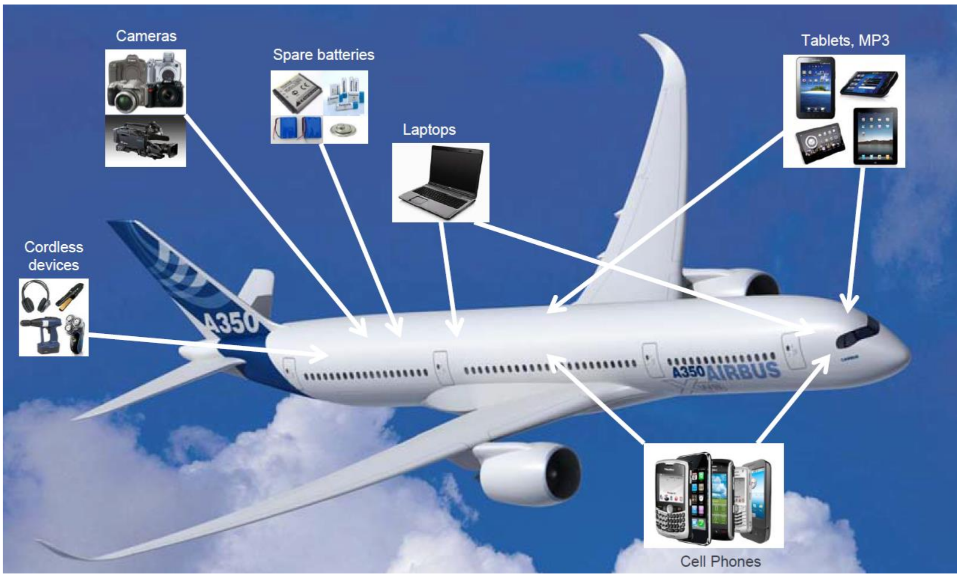

Figure 4.36 – Batteries in the cabin of an airliner

By accident of intentionally triggered thermal runaway of Li-ion cells occur due to devices carried by passengers in an aircraft cabin (Figure 4.36).

5.3) Li-ion batteries in the cargo area[8]

Figure 4.37 – Cargo with batteries that can cause safety risks

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[7] Airbus, 18th Flight safety conference Berlin, 19-22 March 2012

[8] Airbus, 18th Flight safety conference berlin, 19-22 March 2012

Shipping lithium batteries has 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 on-board 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 fire extinguishing agent in cargo holds or engines, is insufficient to stop the thermal runaway and prevent propagation to adjacent cells.

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 querosene 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 the 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 – PROPERTIES OF POTENTIAL ALTERNATIVE FUEL

The European Commission, Airbus, and high-level representatives of the Aviation and Biofuel producer's 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[9] is shown in the Table 4.14:

[9] (https://ec.europa.eu/energy/sites/ener/files/20110622_biofuels_flight_path_launch.pdf).

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 4.14 - Objectives, tasks, and milestones of European Advanced Biofuels Flightpath

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 the 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.

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[10].

- <u>Synthetic Fischer-Tropsch (FT) Based Kerosene Produced Through Biomass Gasification</u>

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 material11. 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.

- <u>Hydrogenated Esters and Fatty Acids (HEFA) and Hydrogenated</u>

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 hydro processing 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 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.

- <u>Pyrolysis Oils (HPO) Produced from Lignocellulosic Biomass.</u>

HPO is still at 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.

- <u>Alcohol to Jet (ATJ)</u>

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[10] https://ec.europa.eu/energy/sites/ener/files/20130911_a_performing_biofuels_supply_chain.pdf

[11] 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

The alcohol to jet (ATJ) is characterised by the production of alcohols as an intermediate product derived from biomass as shown in the Figure 4.38:

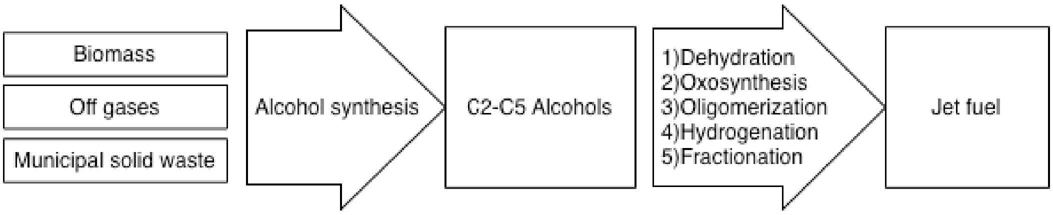


Figure 4.38 - Possible pathways to obtain ATJ biofuel. Source "2 million tons per year: A performing biofuels supply chain for EU aviation - August 2013 Update http://ec.europa.eu/energy/technology/events/2011_05_18_biofuels_in_aviation_en.htm)

The overall process consists of alcohol synthesis from the raw materials followed by chemical synthesis into jet fuel. An advantage of the 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 a 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 under way.

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 effecting 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 to 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" [12](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 biojet fuel blend (below 3%), which corresponds to about 60,000 flights and about 6 million of

[12] http://www.itaka-project.eu/nav/pages/progress_results_7.aspx

passengers. The biojet 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 to biojet fuel in Finland. Camelina plantations have been cultivated in a wide range of climatic and soil conditions. As 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 the 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 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 biojet 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 biojet 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 were 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 decreased up to 1% (saving fuel and CO_2 emissions), and the emitted particulate matter (PM) decreased up to a 50% for a 50:50 fuel blend. PM emissions are a major air quality concern that are linked with a significant number of premature deaths across Europe. High paraffinic fuels such as HEFA biojet could significantly help to reduce the impact of this pollutant in the vicinity of airports. The information obtained has been supplied to the International Civil Aviation Organization for the development of future standards for aircraft engines.

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 the goal 15 (section 4.2). 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 interest of airlines to preserve their flight environment and if appropriate some of the millions of flights 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 T4.6 – WEATHER EFFECTS 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 with 2017 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 4.15 – 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 the aviation which is analysed in the goal 15. In this goal, weather and other hazards from 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 CO2 and NOx emissions and the noise disturbances which are analysed in detail in the goal 9.

Finally, within the aviation impact on the atmosphere it is important to assess how the 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 to obtain 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 a series of measures such as those proposed in the following points:

- Aircraft equipped with systems capable of processing 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 other 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 the goals to be achieved. This is called Aviation 4.0 which is part of the upcoming Industry 4.0 revolution. The 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 others 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 airplane, 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 are able to 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 from the sensors can be shared between the ground infrastructures and the aircraft in a quick and reliable manner. 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 to predict 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 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 an evidence of ice crystals presence 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. The Figure 4.39 illustrates the benchmarks discussed for goal 13

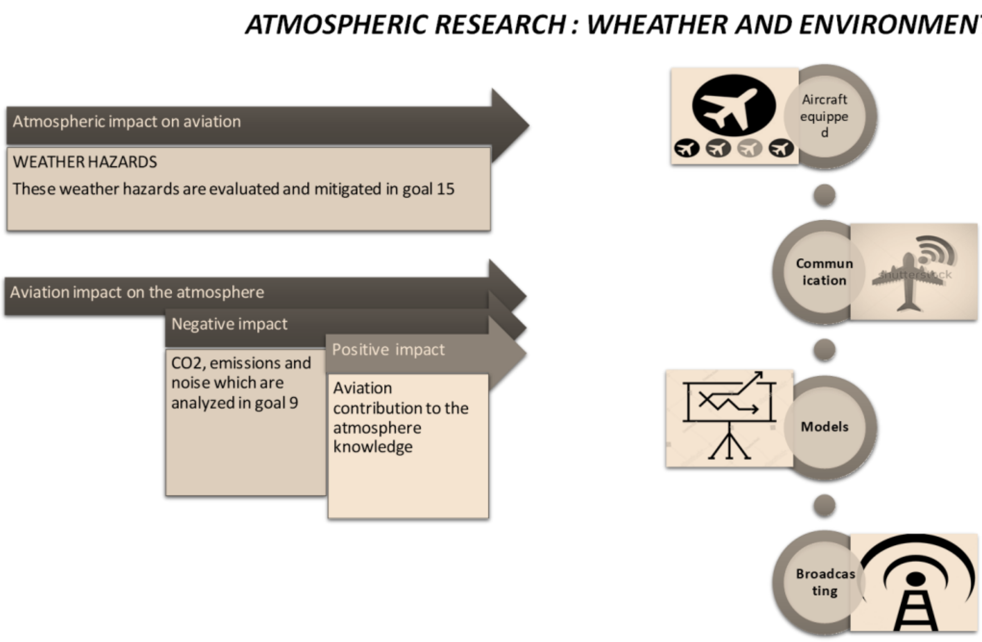


Figure 4.39 - Benchmarks for goal 13

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 the 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:

- Climate change
- Nature and biodiversity
- Natural resources and waste
- Health and quality of life

➢ 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 4.16:

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 4.16 – 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 4.17):

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 4.17 – Endangered species and ecosystem

- <u>Natural Resources and Waste</u>

Environmental regulation has increased resource efficiency through a relative decoupling of resource use, and waste generation (Table 4.18):

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 4.18 – Waste generation and management

- <u>Environmental and Health</u>

Water and air pollution have declined but not enough to achieve good ecological quality in all water bodies or to ensure good air quality in all urban areas (Table 4.19):

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 salt water intrusion.**
Air quality	the quality of air over populated areas is of continuing concern as the degradation of air quality has a major impact on human health, agricultural productivity and natural ecosystems

Table 4.19 – Water and Air quality

All these environmental issues result in climate risks and impacts for aviation which are shown in the following Table 4.20:

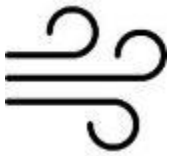
Climate risks	Impact
Precipitation change 	disruption to operations (for example airfield flooding) reduction in airport throughput inadequate drainage system capacity inundation of underground infrastructure (e.g. electrical) inundation of ground transport access (passengers and staff)
Temperature change 	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 4.20– 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 the objective of facing these issues and to develop mitigation strategies.

There are several methods to monitor the atmosphere with the objective 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.

There are several initiatives that 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 atmosphere 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 form 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 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 on board research aircraft.

As it 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, this type of measures is really important since the global climate change represents one of the most serious environmental issue 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, have been in development for several years. On the other hand, the main environmental issues described before (such as climate change), that concerns 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 provides better predictions.
- Improving global, regional and local long-term climate forecasts
- Observing atmospheric additional parameters
- There are 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 with the objective of mitigating 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 4.21 it is shown the main climate risks, their effects and their impact for European aviation. It covered a time horizon up until 2050, a period where initial impacts may begin to be experienced by the industry.

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 4.21– Environmental issues and their implications for aviation

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 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 region as shown in the Figures 4.40 and 4.41:

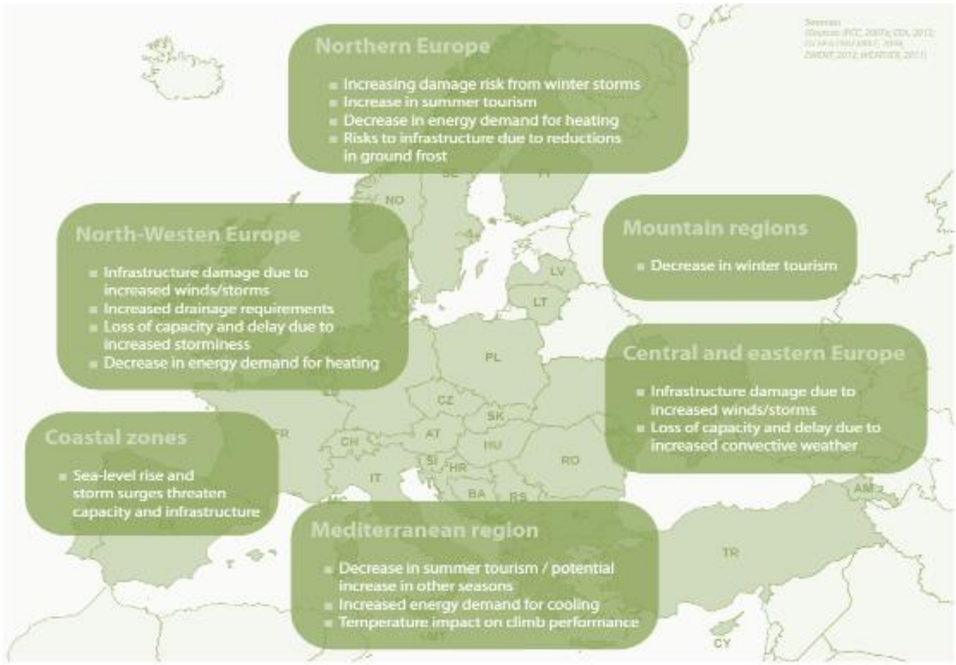


Figure 4.40– Environmental issues effects by region

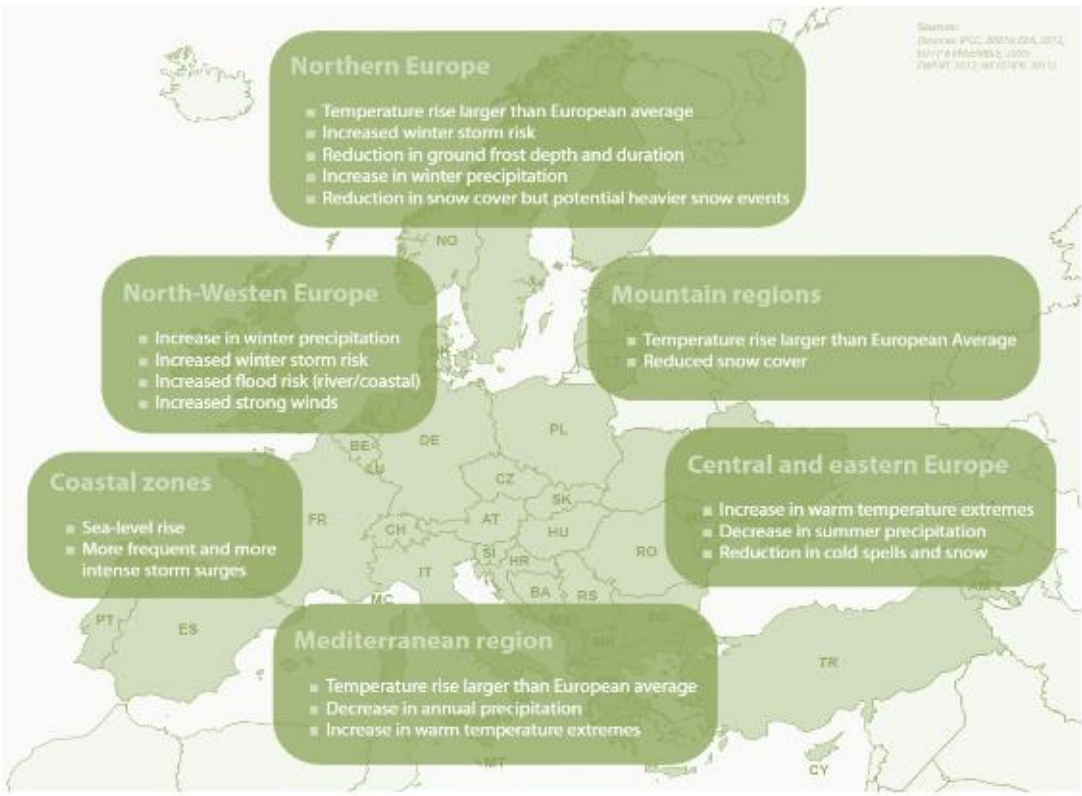


Figure 4.41– Environmental issues impacts on aviation by region

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 aviation industry. It is expected that the environmental issues will predominantly affect infrastructure and operations (Table 4.22). However, some impacts may not be a concern until the middle of the century while others may be experienced sooner.

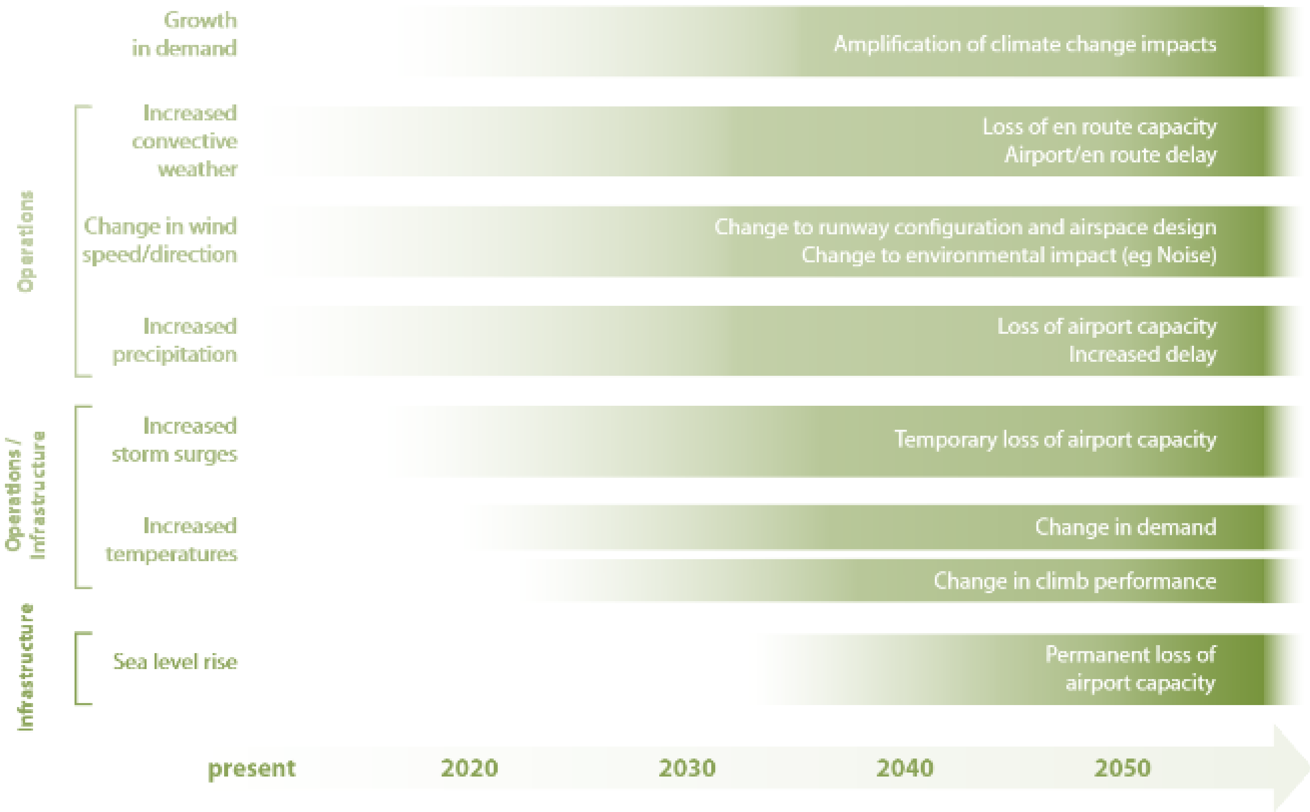


Table 4.22– Effects of climate change on aviation

Atmosphere Composition

In order to face the environmental issues mentioned previously, it is essential to have a better knowledge of the atmosphere composition in order to achieve better forecasts and predictions that would allow to develop mitigation strategies. There are several initiatives and projects which are currently in development and they are expected to progress significantly in 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 in order 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 4.42:

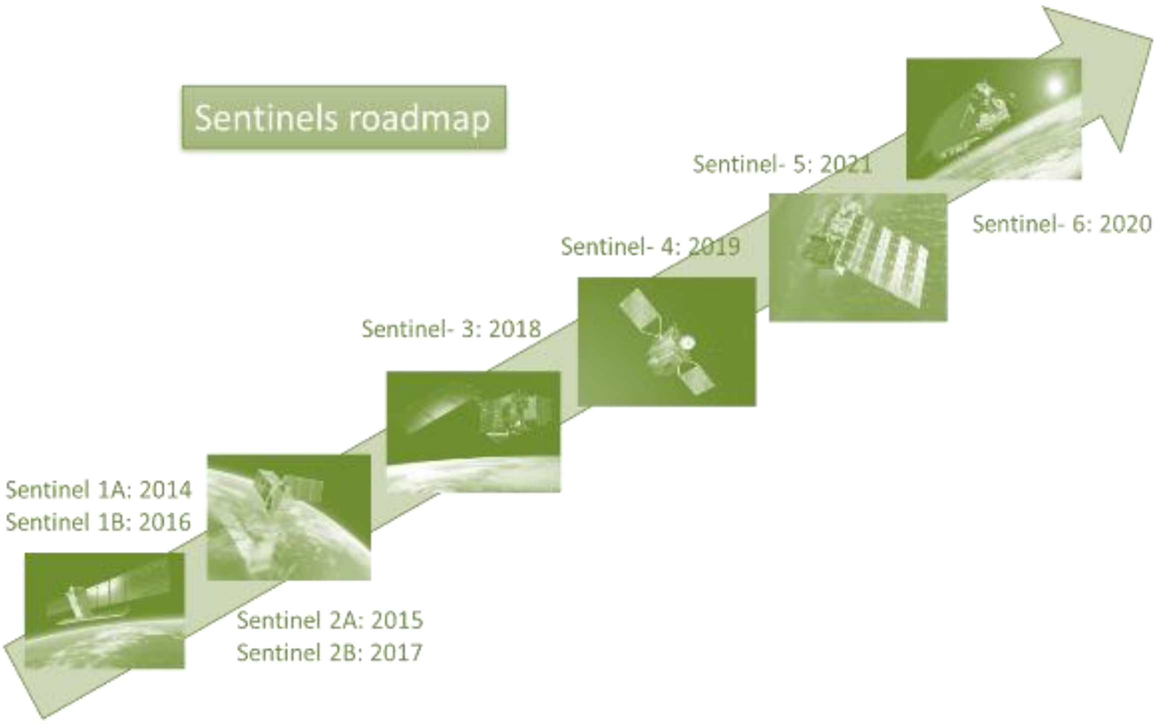


Figure 4.42– The Sentinel families of European environmental satellites

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, 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 on 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 4.43).

As it can be seen, the launch of new satellites will provide better predictions and measurements of the atmosphere thanks to new advanced instruments and techniques.

Sentinels Projection

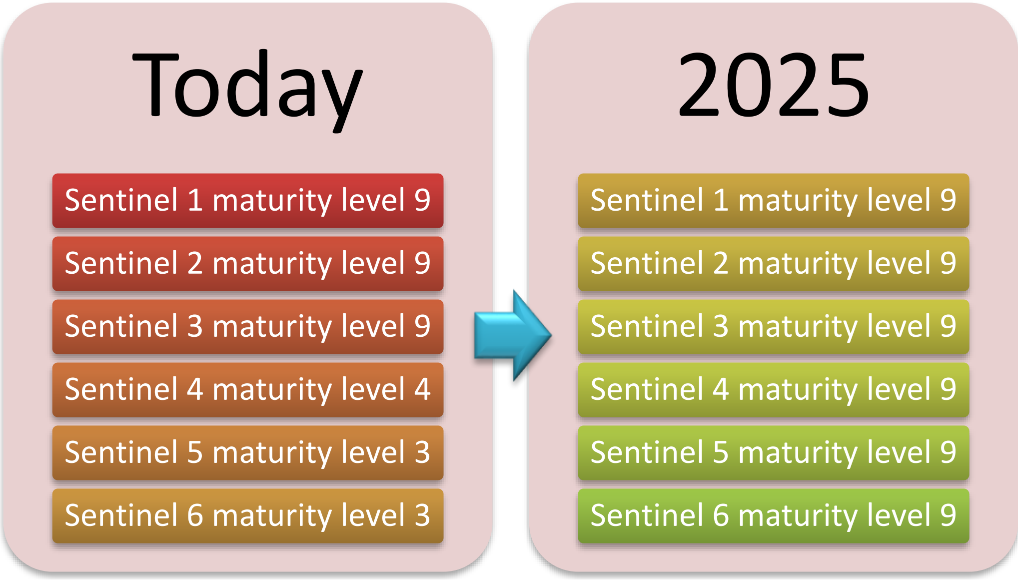


Figure 4.43– Maturity Plan for the Sentinel family.

- COSMIC Mission

New research indicates that the COSMIC microsatellite system (Figure 4.45), which uses a technology known as GPS radio occultation to observe remote regions of the atmosphere, can significantly improve predictions of climate.

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.

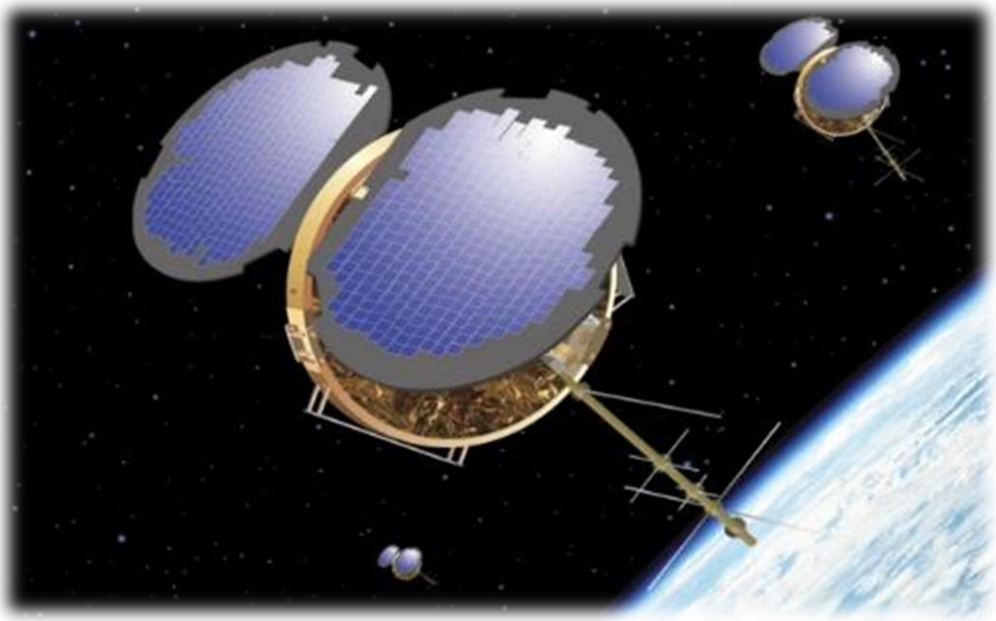


Figure 4.44– Cosmic microsatellite system

Applications:

Weather

- Improve global weather analyses, particularly over data-void areas (such as oceans and polar regions);
- Improve skill 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 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 4.45)

- Develop satellite-based information that will aid in the real-time nowcasting 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.

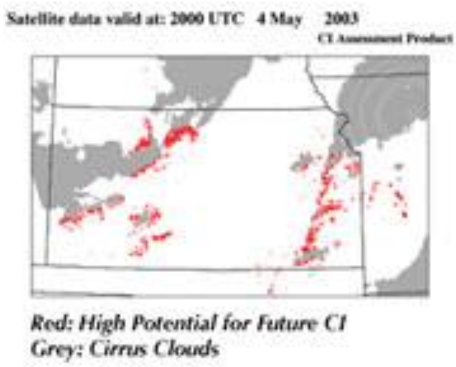


Figure 4.45 – Convective initiation

2. Turbulence Detection (Figure 4.46)

- 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.

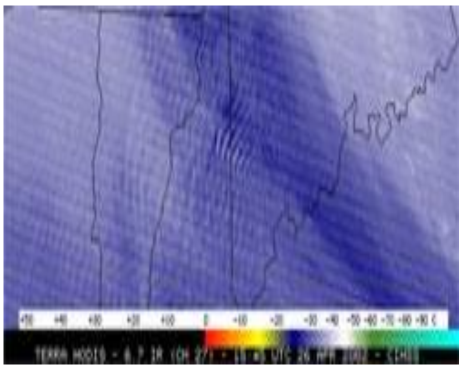


Figure 4.46 – Turbulence Detection

3. Oceanic Weather (Figure 4.47)

- 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.

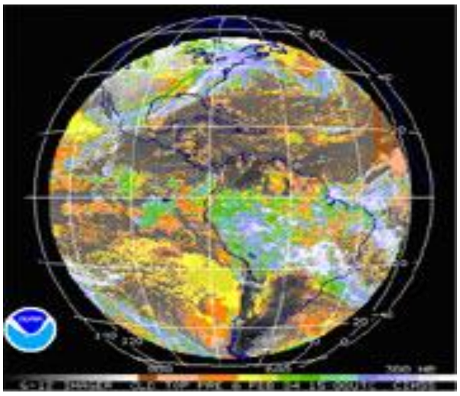


Figure 4.47 – Oceanic Weather

4. Cloud Properties (Figure 4.48)

- 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.

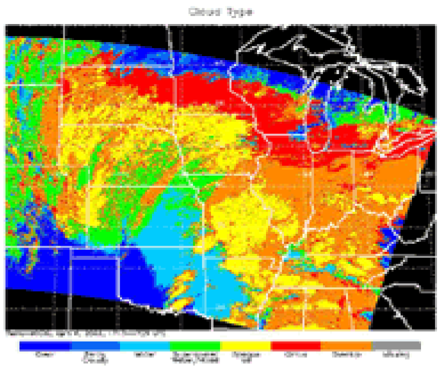


Figure 4.89 – Cloud properties

5. Volcanic Ash (Figure 4.49)

- Develop satellite-based information that will aid in the real-time diagnosis of volcanic ash, ash clouds and ash characteristics.
- Emphasize use of MODIS imagery and other high-spectral resolution data.

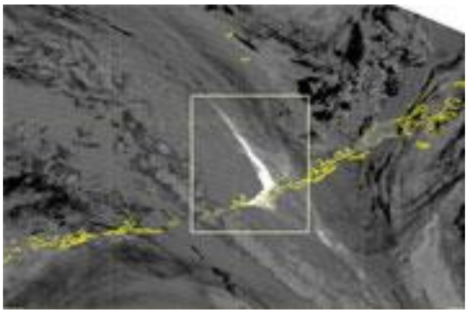


Figure 4.49 – Volcanic Ash

6. Winds (Figure 4.50)

- Incorporate satellite-derived winds to identify possible turbulent regions associated with upper tropospheric jets.

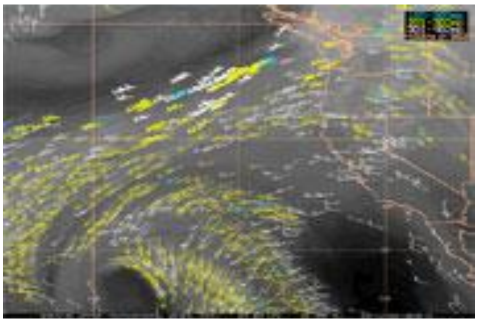


Figure 4.50 – Winds

➢ 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 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 4.52) 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 (Figure 4.53) was fully approved by 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 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 consequence, better predictions and forecasts.

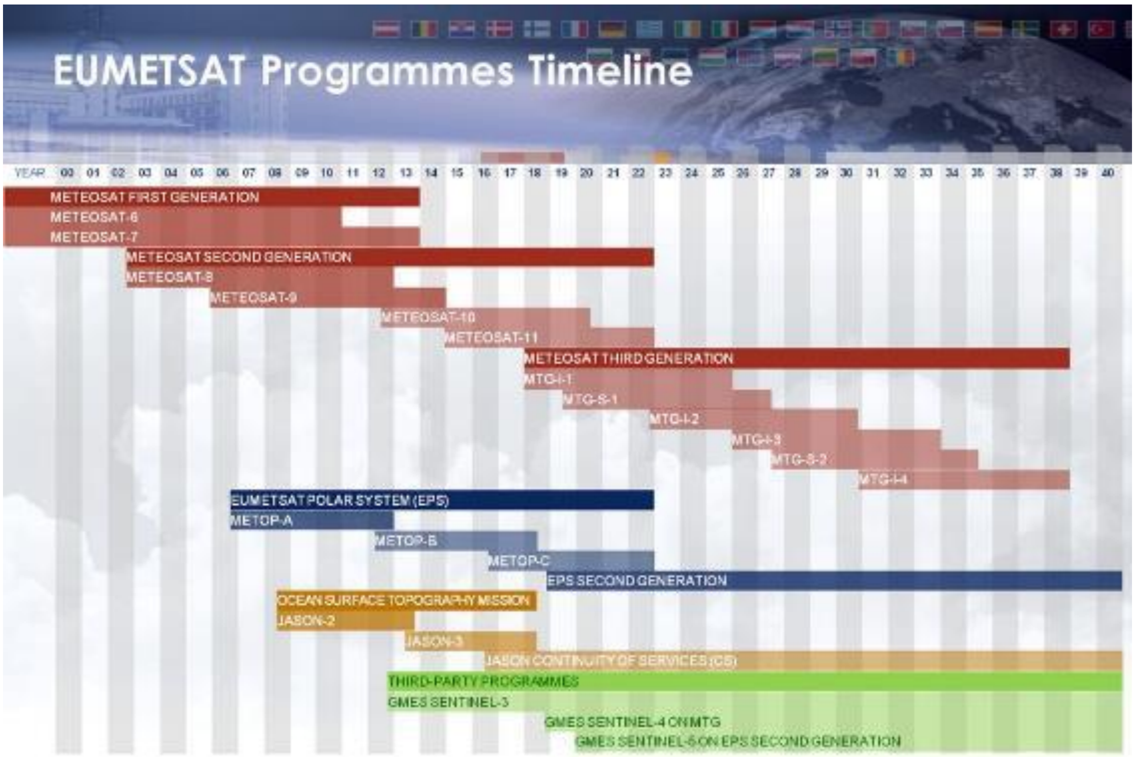


Figure 4.51 – Successive generation of EUMETSAT

- The EUMETSAT Polar System Second Generation (EPS-SG) is the second pillar (Figure 4.54) of EUMETSAT's future, expected to continue the global observations of EPS in the 2020-2040 timeframe. 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 timeframe. In the next image it can be seen the overview of EUMETSAT programs, with all the satellites programme launches:

Meteosat Third Generation Projection:

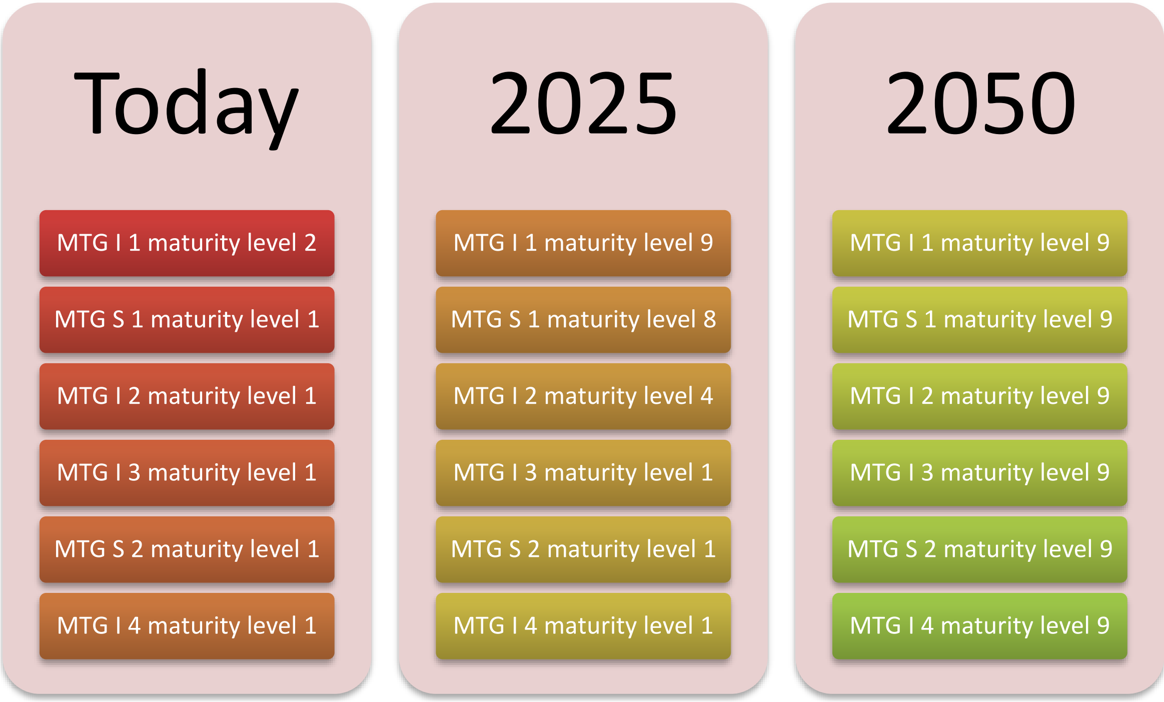


Figure 4.52 – Meteosat Third Generation Satellite Maturity Plan

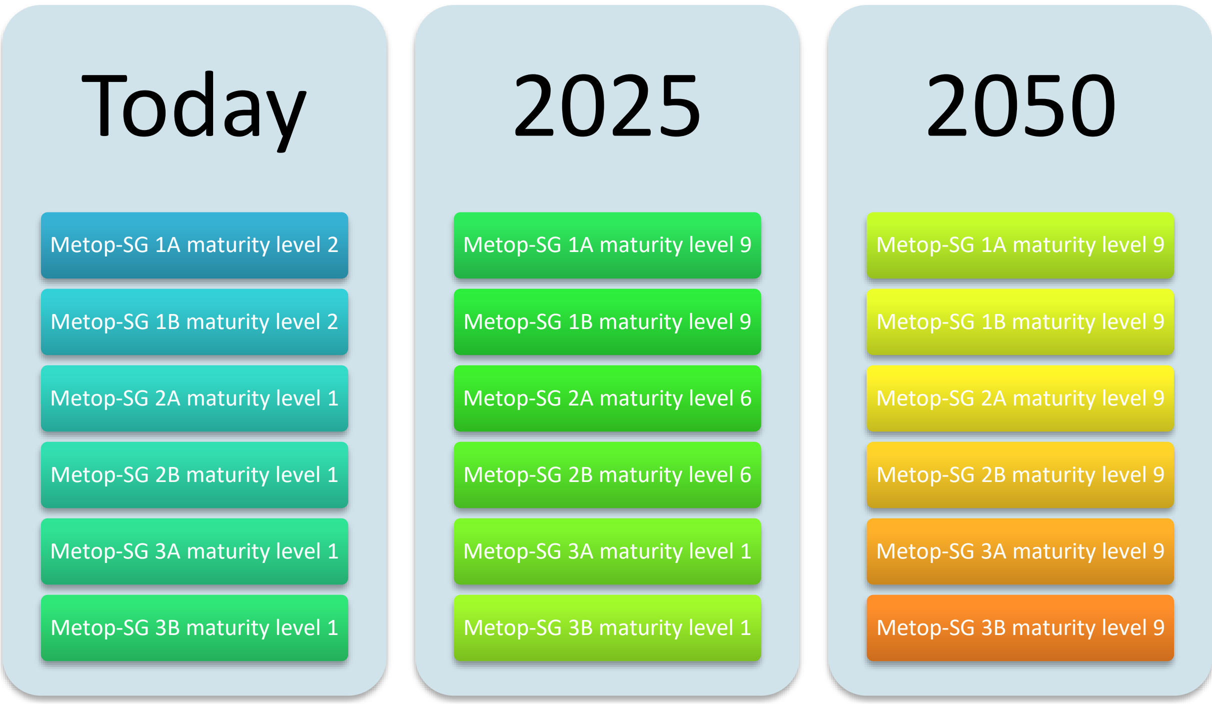


Figure 4.53 - Polar System Second Generation (EPS-SG) Projection

In the next image (Figure 4.54), it can be seen the data that will be provided by monitoring satellites mentioned before:

Figure 4.54 – Image obtained by several environmental satellite systems

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.

In the following image (Figure 4.55), it can be seen examples of installation of IAGOS-CORE instrumentation aboard aircraft:

Figure 4.55 – Instrumentation installed in aircraft for environmental purpose

At the present time, eight aircraft are flying for IAGOS (one with IAGOS-CARIBIC and seven with IAGOS-CORE). Therefore, the technology for monitoring atmosphere through on-board system already exists and the objective is to expand this technology. That is to say, the purpose for 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.

Timeline Projection:

As the technology has already been deployment, the corresponding TRL is the 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 the Figure 4.56:

Figure 4.56 – Expected growth in the size of the fleet of aircraft equipped with IAGOS instrumentation

The IAGOS project is only one of several projects which use aircraft on board systems to measure the atmosphere 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 accuracy and reliable. 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.

Breakthrough Measures to Monitor Atmosphere

In the future, there are 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 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.

➢ On Board Instrumentation

The IAGOS project described previously is only one of several projects which use aircraft on-board systems to measure the atmosphere 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, equipping aircraft in a massive way 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, the 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 the 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 can fly 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, 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 4.57) 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 ash fall 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.

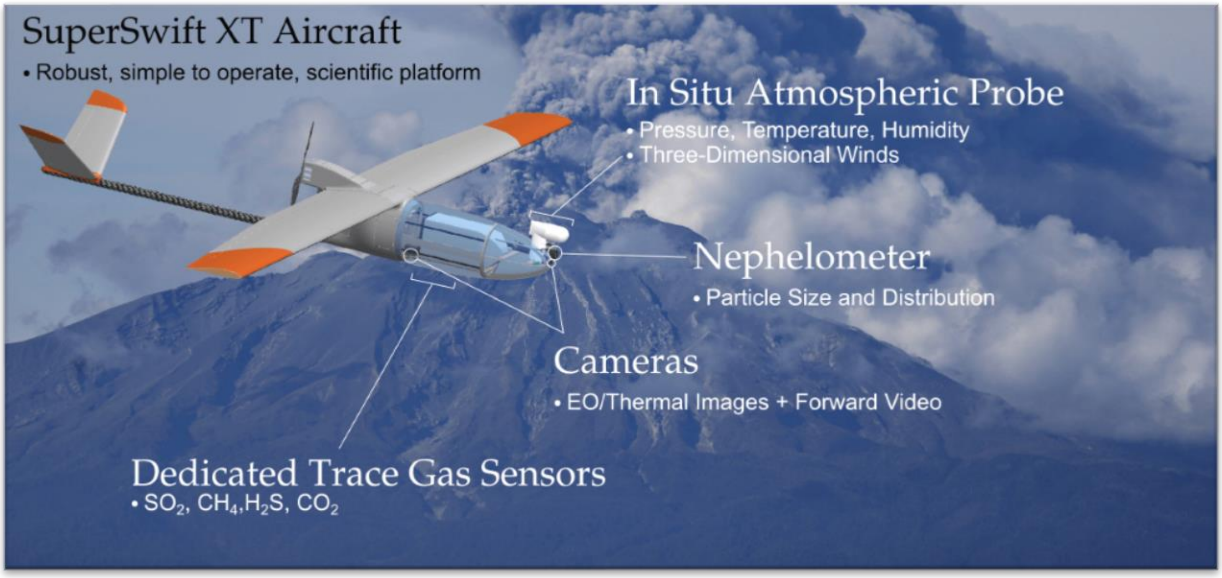


Figure 4.57 – An UAV designed for environmental monitoring in hazardous conditions

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 on-board archive and ground station archive points to facilitate operational activities, ensure protection and minimize data loss.

In the following Table 4.23 it is shown a subset of the capabilities that an unmanned aircraft system could contain:

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 4.23 – Capabilities expected of an UAV designed for environmental monitoring

However, the use if unmanned aircraft systems to monitor atmosphere will have to address several risks:

The drones will have to operate in an 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.

Due to the 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 atmosphere will have lot of benefits that will allow to develop 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.

- <u>Cognitive intelligence for weather prediction: The weather company.</u>

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 atmosphere in recent years. It has allowed to dispose 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 billon individual forecasts daily. Meteorological insights are drawn from satellites, weather stations, planes, radar, terminal and en route 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 4.59) through:

- On-board software that automatically and objectively measures and immediately reports turbulence events using existing airplane 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.

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;
- 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 to develop better prediction models, decreasing damages caused to aviation due to weather conditions.

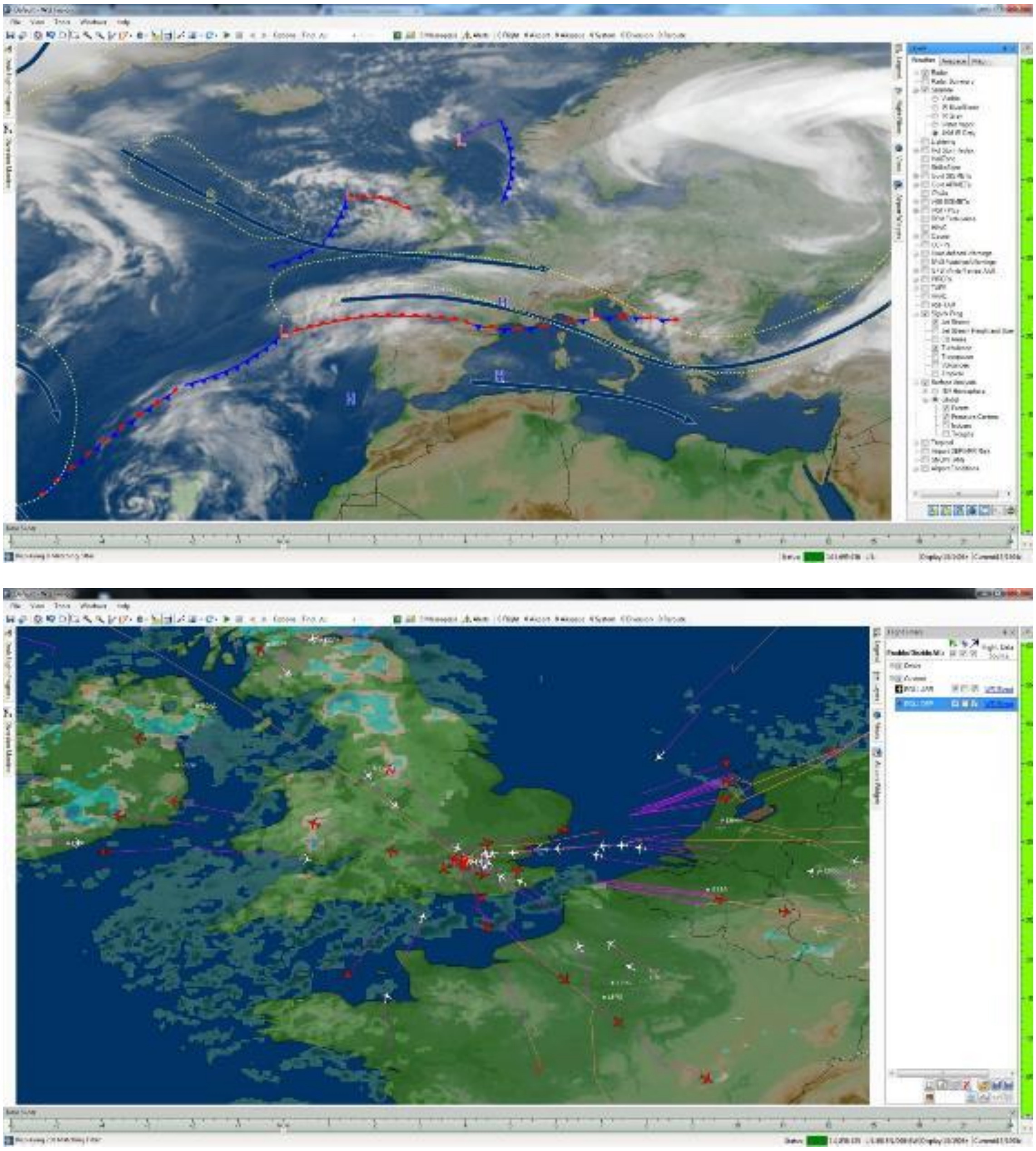


Figure 4.58 – Weather alert available for aviation