Perspectives for Aeronautical Research in Europe

2019 Report

CHAPTER 4

Protecting the Environment and the Energy Supply

Final Report

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Chapter 4 - Protecting the environment and the energy supply

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

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

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

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

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

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

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 CO_2 emissions from air transport:

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

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

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

For that latest ICAO Assembly adopted three environmental resolutions [ICAO Resolution 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) to assist in the further development of Standards, Recommended

Practices and Procedures and/or guidance material on aircraft noise and engine emissions to assist States in efficiently implementing them.

The degree of change makes the future more uncertain, but it also makes the technology program and timing described in this section key if results are to be achieved by 2050. It is also essential that this technology roadmap and its implementation continue to receive support through government policy and that it remains a priority for European society (Table 4.1).

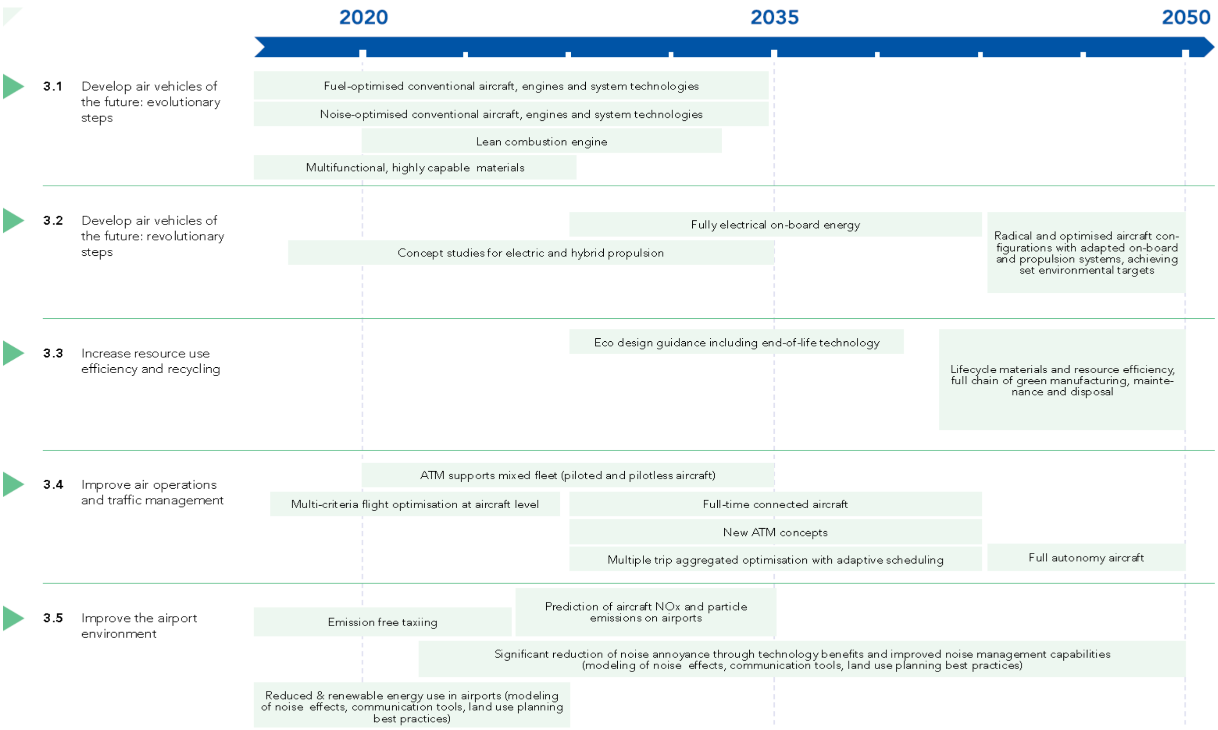
No	Action area	2050 target state	Impact
3.1	Develop air vehicles of the future: evolutionary steps	These actions result in evolutionary aircraft developments that have driven progress in environmental performance towards FP2050 goals. Changes are introduced both into new aircraft and by retrofit across the civil aerospace fleet.	Research and innovation for evolutionary aircraft development described in this action area will drive progress in environmental performance to be on track towards the FP2050 goals. Changes will be introduced in new aircraft or by retrofit into the growing civil aerospace fleet.
3.2	Develop air vehicles of the future: revolutionary steps	New technologies have been developed and implemented that significantly surpass the capabilities of earlier-generation aircraft whilst improving on the high levels of reliability, safety and usability that customers demand.	New technologies will significantly surpass the capabilities of today's aircraft whilst maintaining or improving on the high levels of reliability, safety and usability that customers demand.
3.3	Increase resource use efficiency and recycling	Resources, materials and new processes are better focused on providing an aviation sector that is sustainable. End-of-service is characterized by high recyclability and reuse.	The proposed actions will ensure the development of sustainable aeronautical products through increased recyclability and reuse at the end of service life to ensure better use of resources, materials and processes
3.4	Improve the environmental performance of air operations and traffic management	New operational practices are implemented resulting in optimised trajectories and reduced fuel-burn per flight in accordance with FP2050 goals. The FP2050 goal of emission-free taxiing is well on the way to being realised.	The operational gains resulting from these research activities will induce a reduction of between 250kg and 500kg of fuel (800kg to 1600kg of CO2) per flight - 5-10% of the total - as a major contribution towards the Flightpath 2050 goal of a 75% reduction. This includes a 30% reduction in taxiing fuel-burn per flight due to advanced taxiing operations in pursuit of the goal of emission-free taxiing.

No	Action area	2050 target state	Impact
3.5	Improve the airport environment	Air quality is improved and noise annoyance is reduced to acceptable levels. Airports are fully integrated and accepted by local communities. Intermodal transport connections are efficient and environmentally friendly.	Specific research for the airport environment will permit significant improvement in air quality and reduction of noise annoyance at European airports, with the most appropriate solutions for these key environmental concerns.
3.6	Provide the necessary quantity of affordable alternative energy	Sustainable alternative fuels are widely used contributing to a substantial reduction in aviation's impact on climate change. Disruptive alternatives for energy storage and supply are increasingly viable.	Research and technology results on alternative aviation fuels, in cooperation with the renewable sector and backed by a favourable policy framework, will enable the large-scale deployment of sustainable alternative fuels, which will contribute to a substantial reduction of aviation's climate impact.
3.7	Understand aviation's climate impact	There is a detailed, scientific understanding of the impact of aviation on the climate. This has enabled the introduction of sound, globally harmonized policies and regulations to support climate-friendly flight operations.	Improvements in scientific understanding of aviation climate impact will enable the introduction of scientifically-founded and globally-harmonized policy and regulations to support climate-friendly flight operations, and will highlight the mitigation priorities for manufacturers.
3.8	Adapt to climate change	Impacts of climate change on aviation are well understood and steps have been taken to protect the efficient operations of air transport and the integrity of its infrastructures.	The understanding of climate change risks to aviation, and implementation of measures to tackle them, are essential to facilitate safe and efficient operation of air transport and to protect its infrastructure in the face of increasing impacts.
3.9	Develop incentives and regulations	There exists a comprehensive framework of policy, regulation and incentive to ensure the implementation of new technologies and operations destined to reduce the impact of aviation on climate change.	The implementation of new technologies to reduce the environmental impact of aviation, including a transition to more renewable energies, will only work if embedded in a holistic transport and energy policy framework. Research in this field will deliver these incentives and regulations to support the FP2050 goals.

Table 4.1: The action areas for *Challenge 3* of the ACARE perspectives, transformed from (Strategic Research and Innovation Agenda, 2017)

In recent years the aviation sector has initiated a comprehensive range of measures to mitigate its greenhouse gas emissions. Climate change could pose a significant financial and operational risk for the aviation industry, although there remain uncertainties as to the extent, severity and timing of impacts. The timeline for *Challenge 3* is shown in Figure 4.1 (Strategic Research and Innovation Agenda, 2017).

To achieve the 2050 goals, step changes in aircraft configuration and operation (including alternative energy sources) will be required - currently envisaged evolutions will not be sufficient (Strategic Research and Innovation Agenda, 2017). Such disruptive change will have consequences for all stakeholders: manufacturers, airlines, airports, ANSPs and energy suppliers. ACARE runs three research projects to achieve these goals: X-Noise EV, which relates to aviation noise research, Forum AE, which relates to emissions research, and Core-Jet Fuel, which relates to alternative aviation fuels.



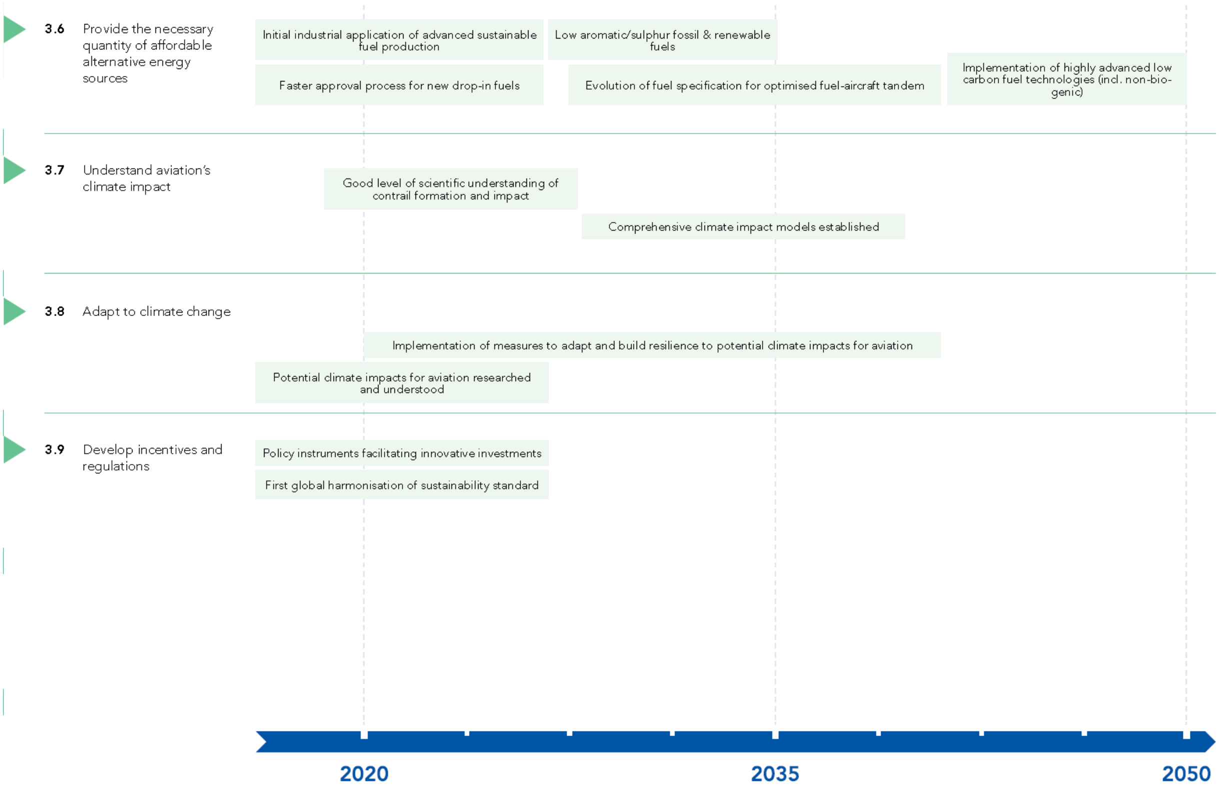


Figure 4.1: Timeline for ***Challenge 3***: Protecting the environment and the energy supply (Strategic Research and Innovation Agenda, 2017)

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.

Unfortunately, aircraft have a large number of noise sources, as illustrated in Figure 4.2. The major sources of engine noise are the fan and jet, and to a lesser extent, the compressors, combustor, turbine and bleeds (which may actually dominate at certain times during flight). Airframe noise is generated by the airflow surrounding the moving plane. The main sources are the discontinuities of the aircraft structure, such as high-lift devices (HLD), landing gear wheels (when extended), and trailing edges which lead to speed shearing (aircraft speed versus still air). A further source of noise arises from the interaction of the engines exhaust jet with the airframe. As a general rule, engine sources dominate on take-off while airframe noise dominates on approach.

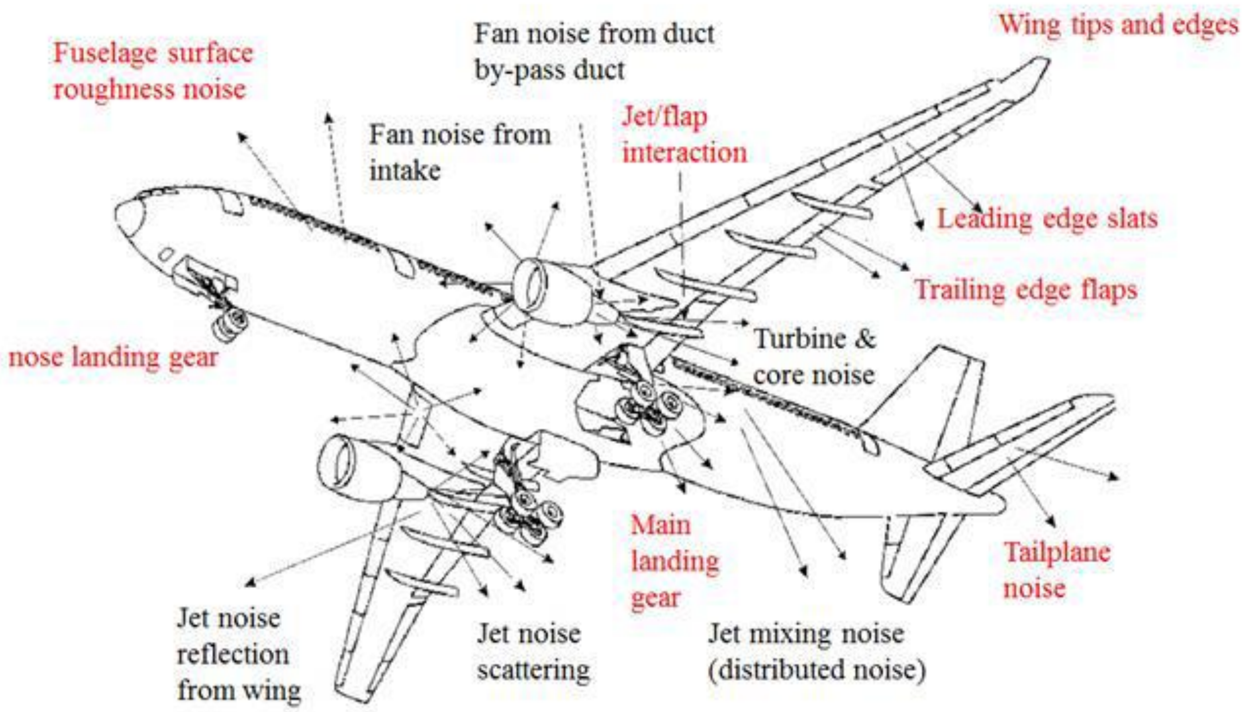


Figure 4.2: Main sources of engine and airframe noise

There is potential for reducing noise by way of better component design and incremental improvements in existing technology, but it is not appropriate to detail all the possibilities here (Table 4.2 is for illustrative examples). Instead, we highlight where new technological improvement is likely, and cases where an improvement in aircraft efficiency and gaseous emissions creates a new noise risk that will need to be addressed. However, they can be broadly classified as engine noise sources and airframe noise sources. The range of liners employed to attenuate noise will be significant in the near term. Specifically, lip liners (where the intake liner is extended around the lip of the nacelle intake) are feasible now that the problem of integrating them with the de-icing system has been overcome. Modern ceramics and improved manufacturing have made core exhaust liners possible, but the problem of high temperatures and a highly curved geometry must still be solved. Equally, ALM allows for varying the depth of nacelle liners to obtain a distribution of acoustic impedance that can be optimised for maximum attenuation (Nark et al., 2016) or the use of radically new liner design (Koch et al., 2017).

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

Table 4.2. Examples of potential noise reduction through component improvements. (Based on data given in (CAEP/9 Meeting, 2013))

4.1.1. Aircraft engine emission

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

The increasing use of electric systems heralds yet further introduction of electric technology, and the commitment of both Airbus and Boeing to electric power is clear with the E-Fan and Horizon X programmes. More broadly, there exist a host of concepts and demonstrators for hybrid electric and fully electric-powered aircraft by a number of new players who have entered the field.

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

Whilst technological improvements targeted at reducing noise and/or gaseous emissions have been made, the main reason for the steady progress in reducing aviation emissions over the last few decades can be directly linked to an overall improvement in aircraft fuel consumption, as illustrated in Figure 4.3.

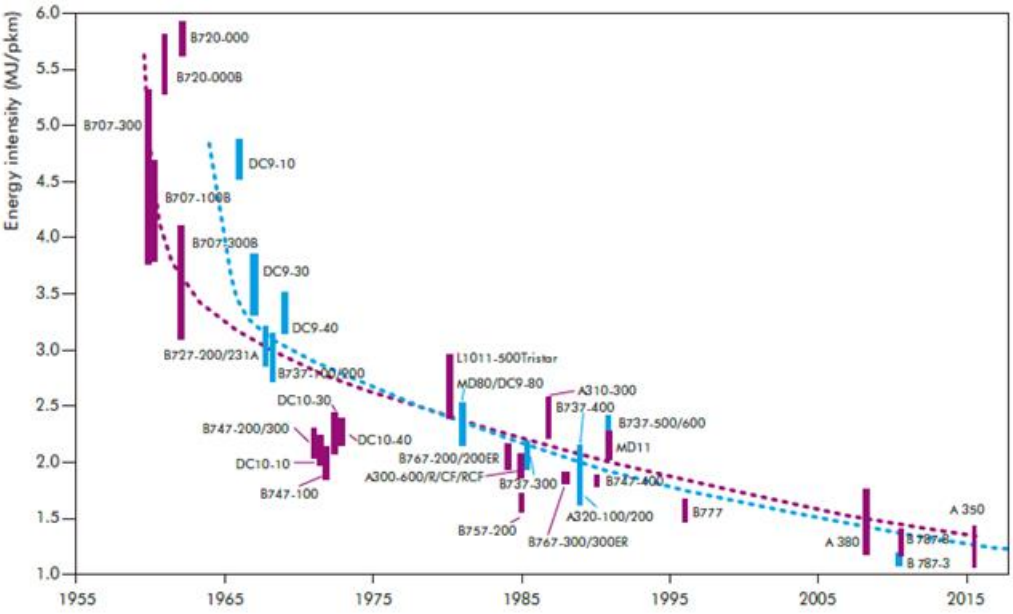


Figure 4.3: Improvement in aircraft efficiency

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

Historically, the greatest increase in aircraft efficiency has been made by improved engine performance. However, as engines have become more efficient, the gains to be made through airframe improvements have become more significant. There are two main points worth noting here. Aircraft weight is a primary driver of fuel burn because a heavier aircraft requires an increased lift, thereby increasing drag and the consequent need for additional thrust. To decrease weight, the use of composite materials (based on carbon fibre or glass fibre) in aircraft has increased in recent decades. A high percentage of newer aircraft such as the Boeing 787 and the Airbus A350 XWB consist of such materials.

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

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

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 its 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.

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

Open rotors, in essence, are turboprop engines with second counter-rotating propeller, which regenerates the flow. Addition of the second step of the propeller makes possible to improve considerably efficiency and high speed of engine operation holding the propeller diameter, which can be built in the airframe. Without a spinner around propellers, the open rotors have a lower potential to provide shielding and releasing noise reduction than turbofan ones. Though the early results of scaled model tests show that the modern design with open rotor can be as much “soft” as current closed turbofans. This potential effect on the perceived noise around airports should be balanced with a potential 30% increase in efficiency of fuel use over modern turbofans (Royal Aeronautical Society, 2005). Open rotors also can be restricted from the technical point in several motion speeds some lower than turbofans (maximum Mach number is equal to 0,75, but not to 0,85 that makes 5-10 minutes of additional flying time). The number of flights, which can be made at short hauls (< 2000 km) per day, does not change considerably; therefore this difference in speed will be acceptable. Nowadays some turbofan air vehicles with short ranges are already slower than M=0,8 in order to save fuel. Long-time air vehicles can still support closed engines, where time, noise and operational problems can avoid application of the open rotor (Parker R., Lathoud M., 2010).

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

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

To reduce the noise level it is supposed to use the noise active control system, which includes acoustic resonators to be installed on blades of the fan outlet straightener and devices based on MEMS-technology and installed along the inner passage of the engine nacelle. The application of such a system makes possible to reduce the noise level in a source by ~50–60% (Fig. 4.4-4.5).

In the work (Czech M.J., Thomas, R.H., Elkoby, R., 2012) there were studied the effects of chevron nozzles of two main types on the noise level, chevron rigging angles (submersion), the effect from a standard pylon, vertical control surfaces of an airframe, elevon and aileron deviation angles.

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

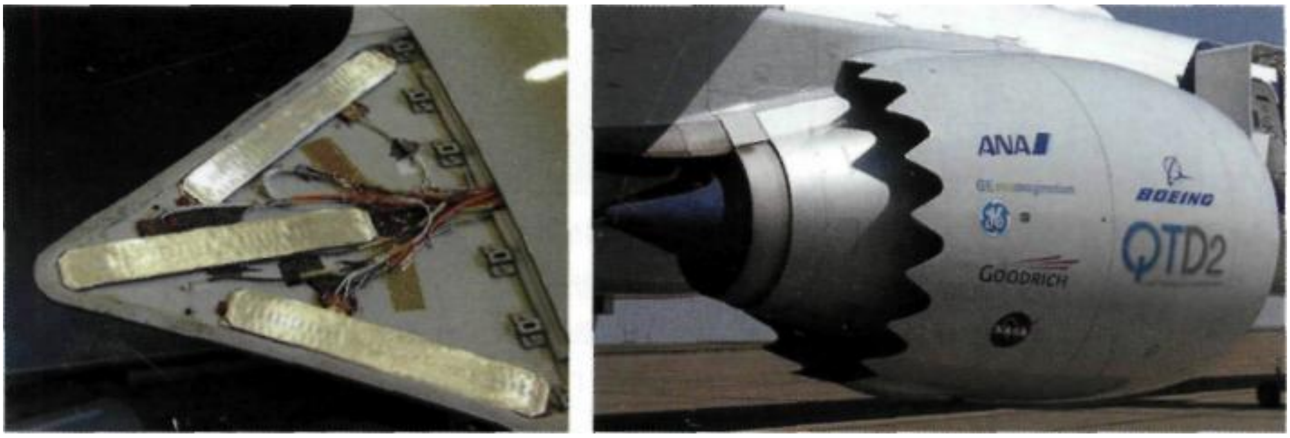


Figure 4.4: Chevron nozzle made of shape memory material

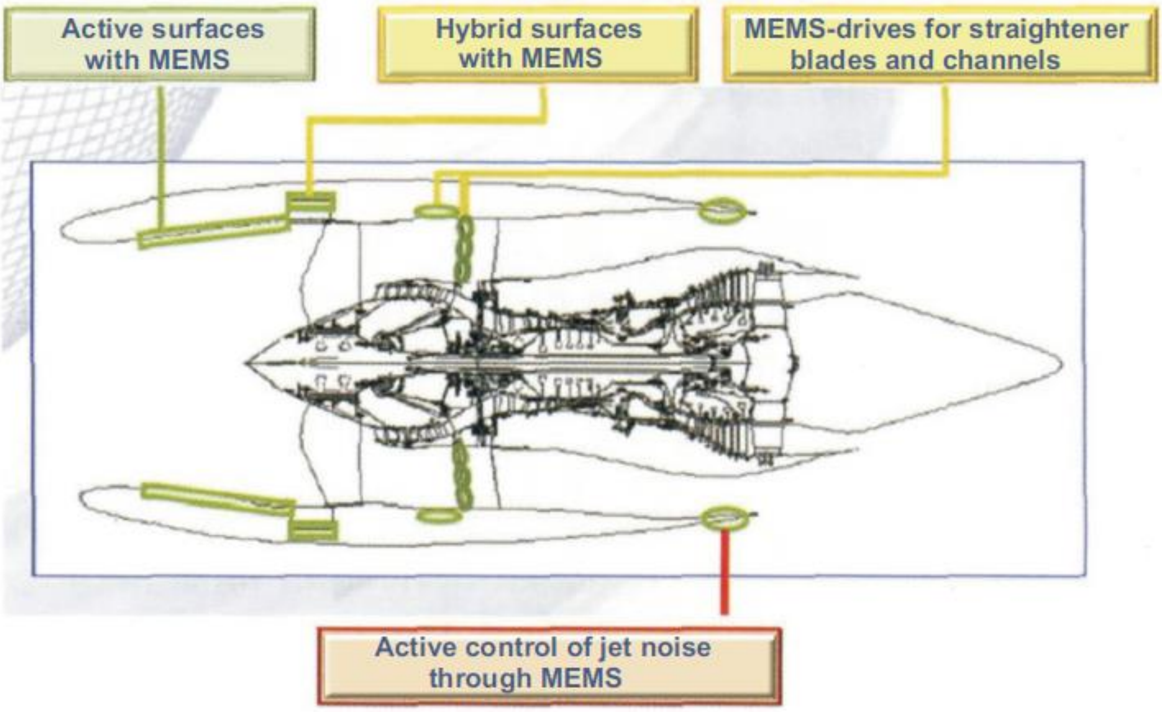


Figure 4.5: Engine noise reduction technologies

When adding the sideline and retraction points more than 6,5EPNdB of reduction of jet noise was achieved by mounting a better common nozzle relatively to an isolated nozzle of the baseline. The better common nozzle contains T-fan chevron (Fig. 4.6) oriented for longer chevrons in an asymmetric pattern from the airframe and ground observer location and the main chevron, which in essence is a homogeneous structure by circumference. This nozzle was selected and manufactured for the experiment with high accuracy in order to obtain the aeroacoustic characteristic of N+2A HWB concept in NASA (Czech M.J., Thomas, R.H., Elkoby, R., 2012).

Figure 4.6: Chevron nozzle, type T-fan

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

The engine with m=7 ran in peculiar cycle periods at static conditions and in flight conditions. Pylon effect and its orientation for jet noise were also studied as a function of bypass ratio and cycle conditions. Adding of the pylon led to considerable spectral changes reducing jet noise up to 4 dB at high polar angles and increasing it by 2-3 dB at direct angles. In order to estimate noise shielding a model scheme to scale was presented so that the jet nozzle was located from the trailing edge to several diameters before the trailing edge of the airframe model. Mounting on two diameters of the fan in front of the wing trailing edge provided only restricted shielding in the first arc at high frequencies either for axially-symmetric nozzle or for the common round one with a pylon. The pylon was additionally modified as for the technology, which inflates air via pylon flange, which is efficient for reduction of low-frequency noise and moving the jet noise sources closer to the nozzle outlet (Fig. 4.7). Further, it is reviewed the concept of the active pylon, where the flow is inflated via the lower part of the thermal flange. Reduction by 1 dB was revealed in mid angles with blow pressure factor. Configuration with a stronger submission of the chevron and pylon oriented opposite to microphones caused the maximum reduction of jet noise. Additionally to the jet noise source the shielding of the wide-band spot noise source was recorded with reduction of the noise level up to 20 dB.

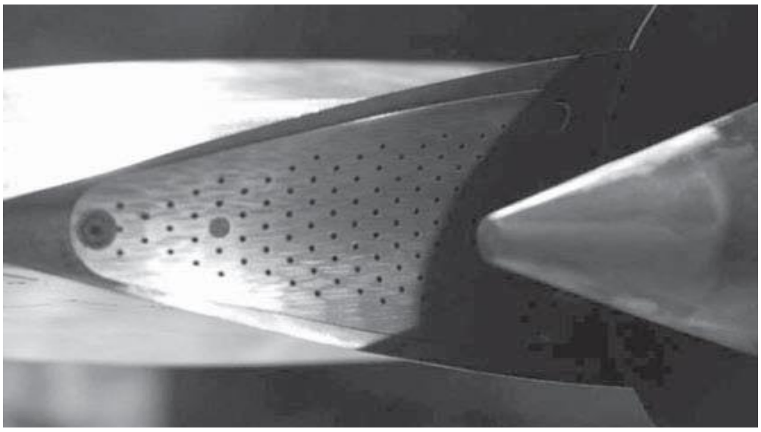


Figure 4.7: Pylon with blowing of gas to the stream

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

In parallel with an evolution largely driven by global environmental issues, there is evidence of increased sensitivity to noise in local communities impacted by aviation operations despite a significant reduction of aircraft source noise over the years. The air transport growth perspectives in Europe are still conditioned by improvements in all three elements of the ICAO Balanced Approach [ICAO Resolution A39-1]. The initial SRA1 approach presiding over the definition the ACARE 2020 noise targets remains valid (Figure 4.8), 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.

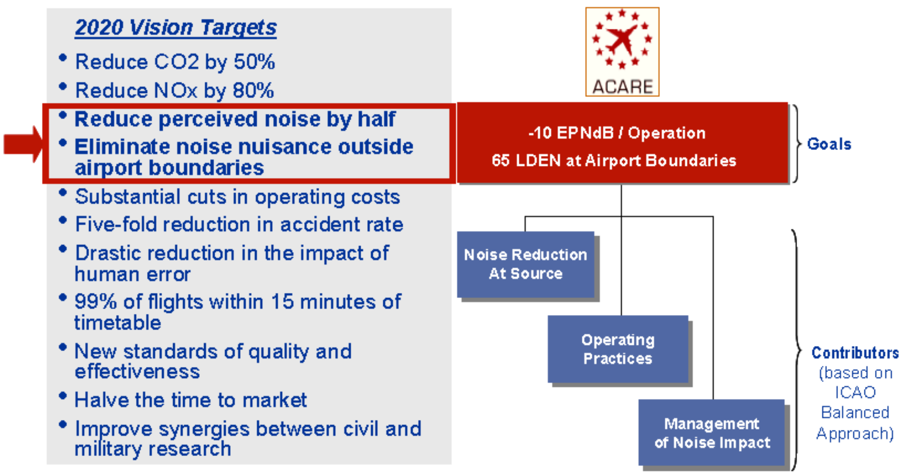


Figure 4.8: ACARE SRA 1: Noise Goals for Fixed-Wing Aircraft

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

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

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

- On the internationally recognised **Technology Readiness Level scale** (Figure 4.9), that allows keeping track of the situation of individual technologies identified in the SRA1.
- On a dedicated process, called **Technology Evaluator**, involving a predictive model with the capability to roll up the benefits of individual technologies at the solution level and establish the progress achieved globally, including operational aspects.

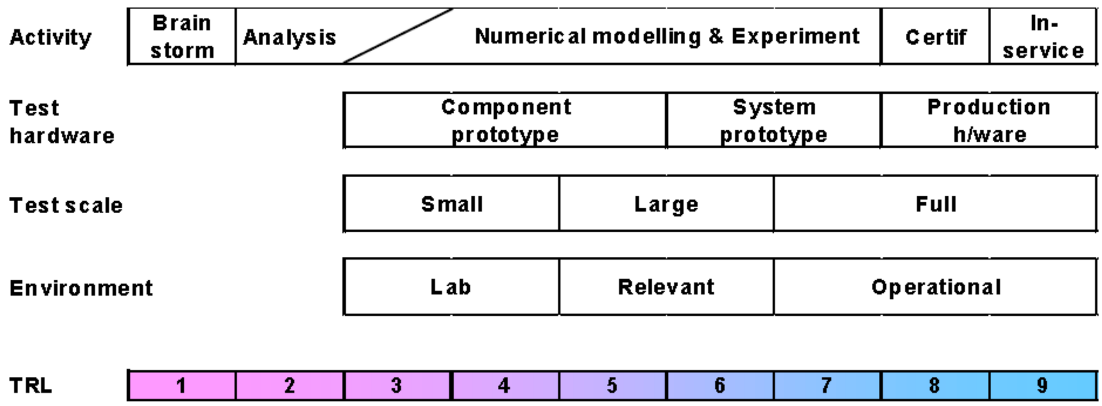


Figure 4.9: Technology Readiness Level Classification (TRL) used for solutions assessment

An approach by consensus based on expert's judgement, assessment of the TRL situation and results from the technology evaluation exercises have then been used to perform the 2015 progress assessment, coming up with updated progress achievement figures and formulating associated recommendations for future research. Recommended Phased Approach to meet ACARE Noise Goal #1 includes analysis of expected advances on noise reduction with Noise Reduction Technology 1 (NRT1) and NRT2, as well as the Noise Abatement Procedure, (Figure 4.10).

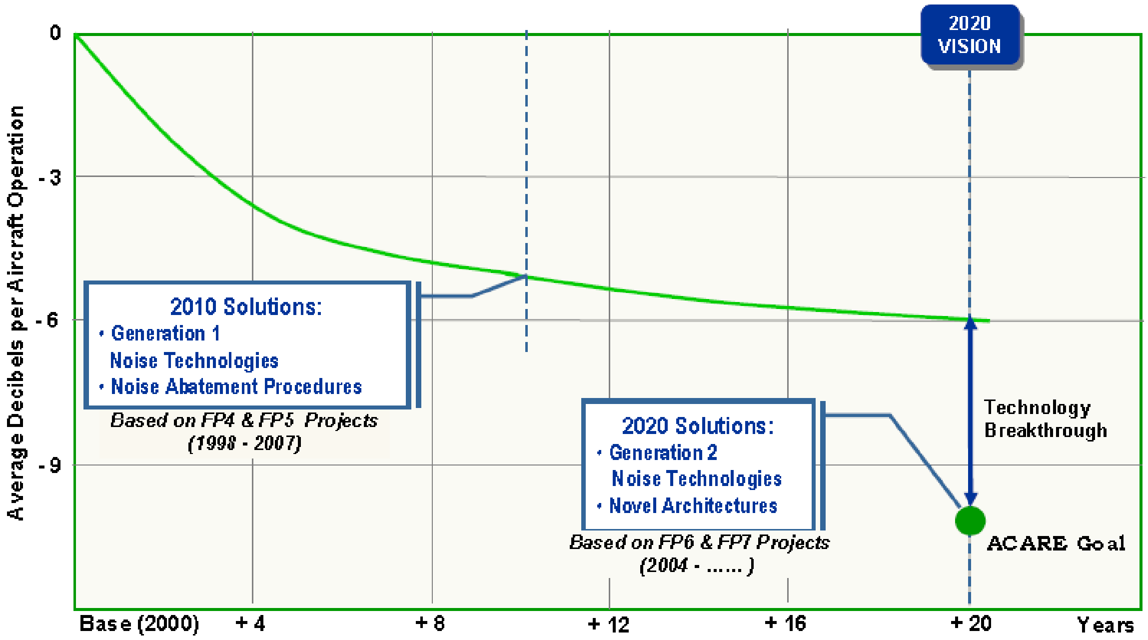
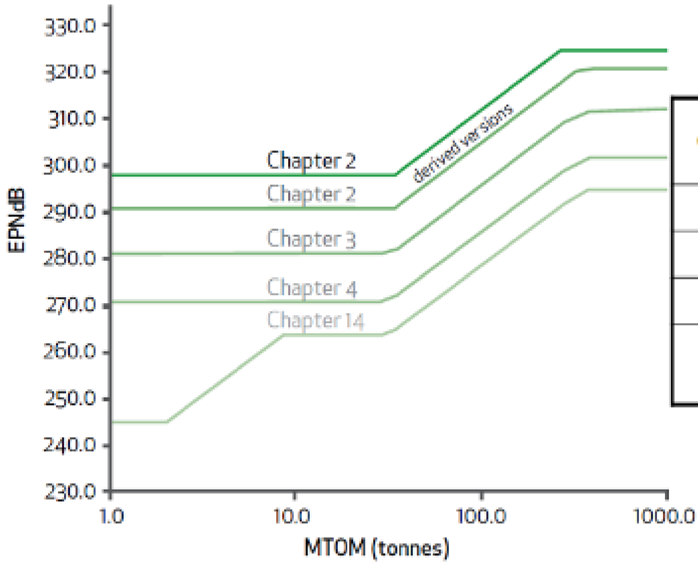


Figure 4.10: Expected advances on noise reduction with NRT1 and NRT2, as well as the Noise Abatement Procedure

Since the year 2000 a number of civil air transport aircraft have been certified by the European industry, a few others, still in their development phase are planned to be certified before 2020. Certification requirements for aircraft noise during this 20 years period were changed twice (Figure 4.11) – in 2006 and 2017, once again basing on NRT1 and NRT2 achievements, reached in EU (Figure 4.12). 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 4.13). The observed average achievement is 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.

At the end of the OPENAIR project, NRT2 have achieved TRL 4/5 (look in Figures 4.9 and 4.13) 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.



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 4.11: Certification requirements for aircraft noise due to ICAO standards

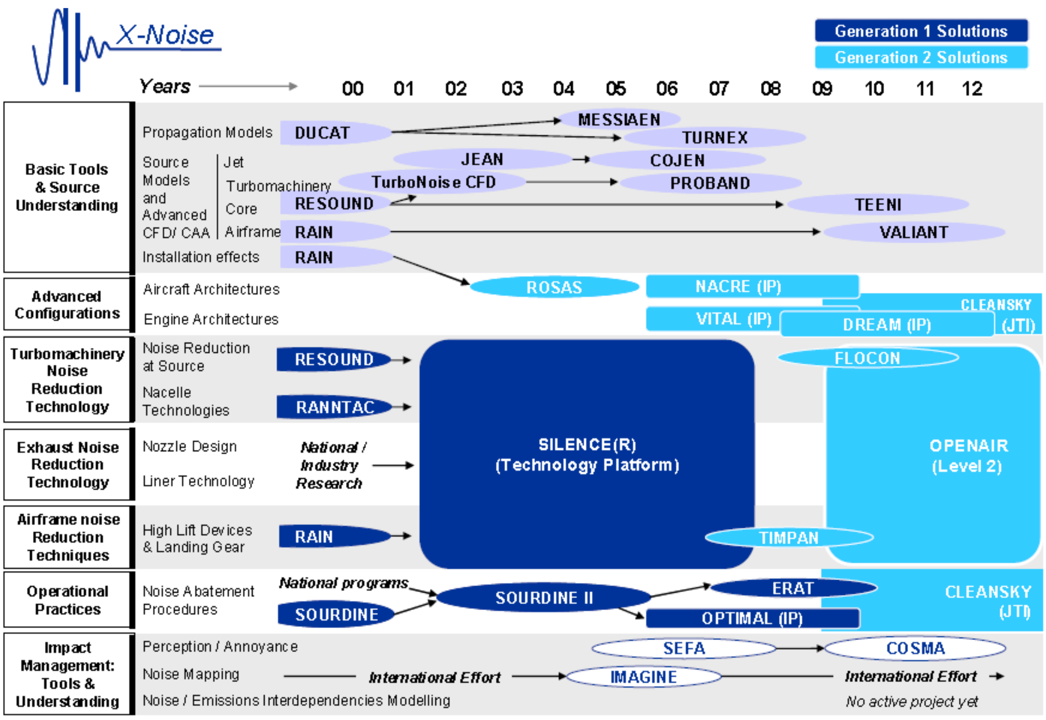


Figure 4.12: Roadmap of EU Aircraft Noise Research Projects vs Key Technical Areas (Generation 1 and 2 solutions - NRT1 and NRT2 performances – were achieved by results of the projects shown and classified in accordance with priority acoustic sources)

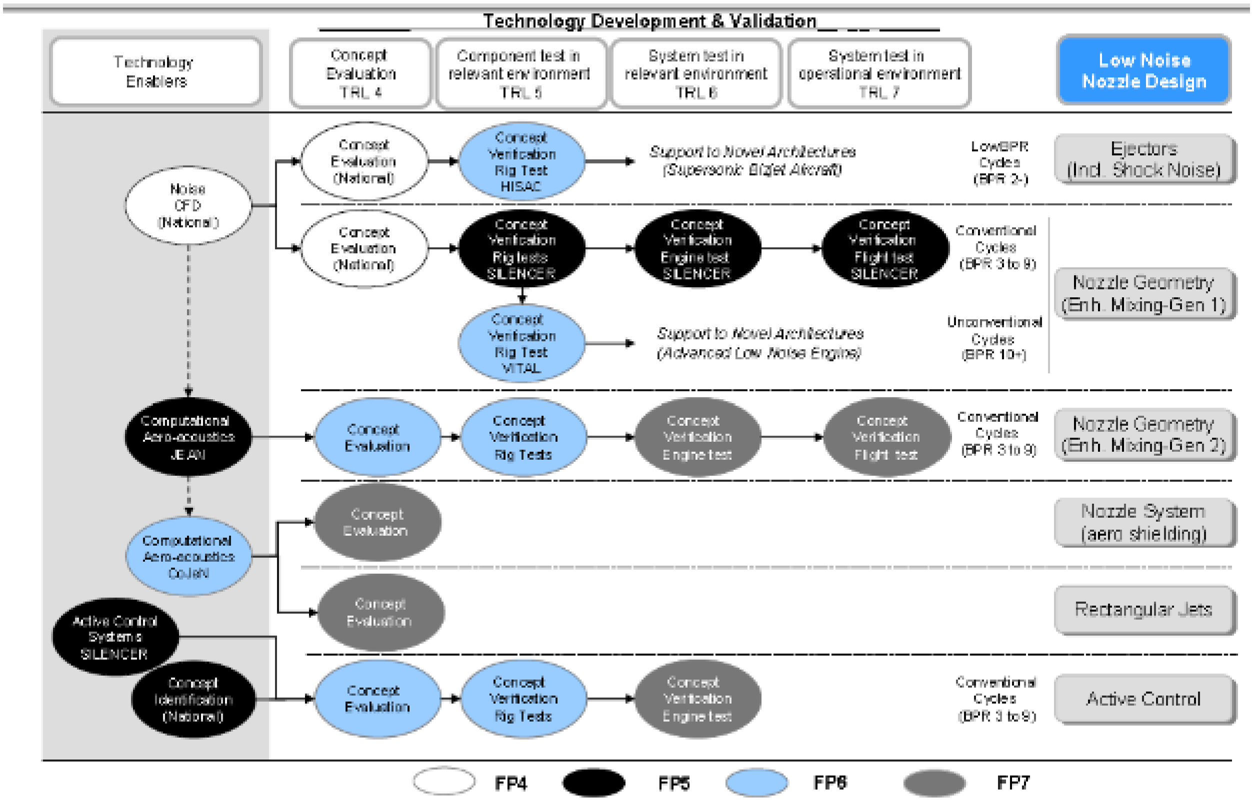


Figure 4.13: Noise Reduction Technologies Development & Validation

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 4.3).

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 4.3: Technology Readiness Level and Technology Status

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

The dominant source of acoustic emission during take-off is the power plant (jet stream and fan) (Figure 4.14) (Leylekian, L., Lebrun, M., Lempereur, P. 2014).

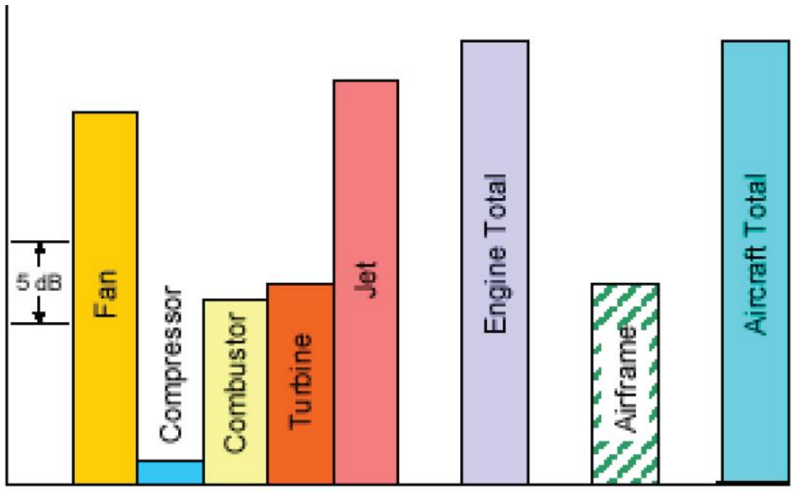


Figure 4.14: Sources of aircraft acoustic emission during take-off

During landing (Figure 4.15), along with the noise of the engine fan, the noise sources are the airframe skin and aeroplane elements (flaps and landing gear) (Leylekian, L., Lebrun, M., Lempereur, P. 2014).

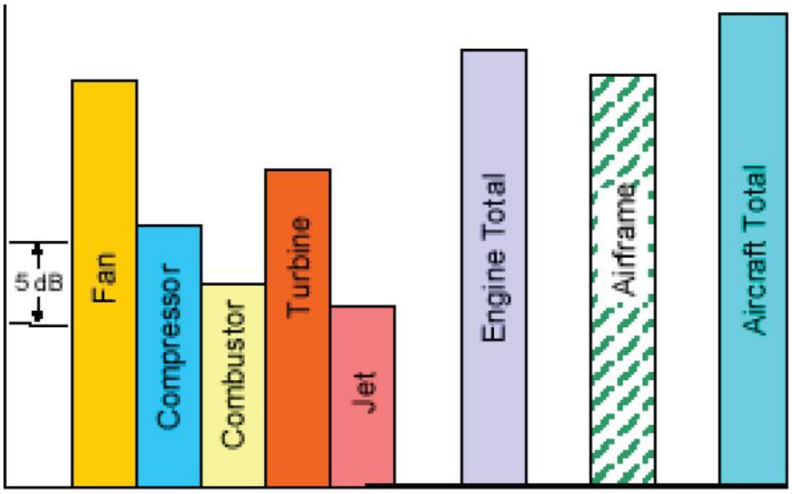


Figure 4.15: Sources of acoustic emission during landing

One of the promising areas is the creation of effective sound-absorbing structures that are used in the engine nacelle (Leylekian, L., Lebrun, M., Lempereur, P. 2014).

Besides, special porous materials are under development, the use of which can reduce the acoustic emission from the source (Delfs, J.W., et al., L. 2017).

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

Let's consider briefly the main directions of new technologies. Rolls-Royce engines have new technologies introduced, providing low noise. Fig. 4.16 shows the compliance of Rolls-Royce engines with modern ICAO requirements (Chapter 14 of Annex 16, vol. 1). The noise reduction in Rolls-Royce engines is provided by increasing the by-pass ratio of the engine, reducing the fan noise, optimizing the engine cycle, using the contra-rotating rotors, using the sound-absorbing structures and reducing the level of turbulence in the inlet section.

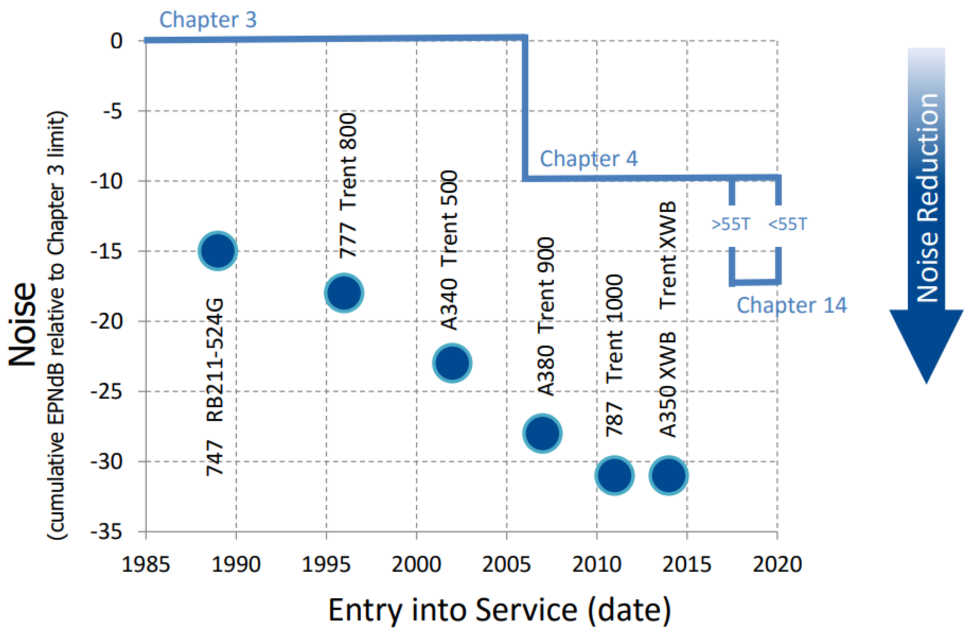


Figure 4.16: The compliance of Rolls-Royce engines with modern ICAO requirements (ICAO Annex 16, vol. 1, Chapters 4 and 14)

Reduction of fan noise is provided by the use of a low-speed advanced fan (reduction of the dipole acoustic noise source). Wide-chord fan blades have a twist in height and are made of composite materials.

Reduction of the acoustic interaction between the fan impeller and the outlet guide vanes is provided by inclined and specially profiled blades, the number of which is selected to provide the "cut-off" effect.

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

Using an inlet section of a special design contributes to the reduction of the turbulence level at the engine inlet, which in turn reduces the level of vortex noise at the fan inlet. Also, acoustic emission reduction is achieved by using sound-absorbing materials and reducing the tonal noise of a low-pressure turbine. A decrease in tonal noise is provided by improved aerodynamics of the turbine blades and a decrease in the rotational frequency. Fig. 4.17 presents a set of technologies in the Rolls Royce engine to reduce noise.

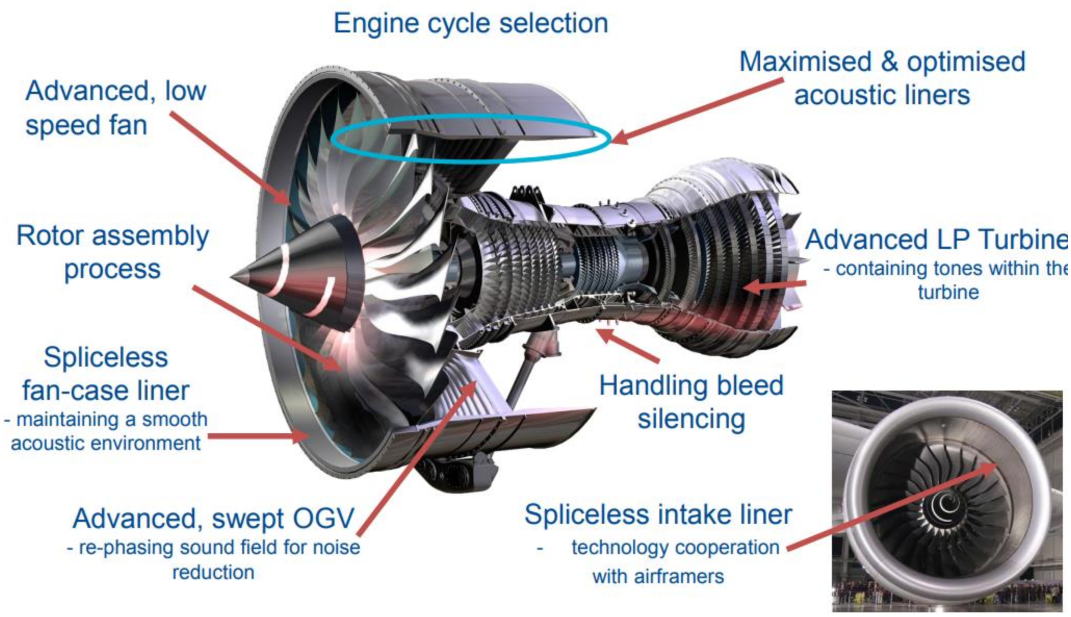


Figure 4.17: Rolls Royce engine noise reduction technologies

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

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

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

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

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

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

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

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

To maintain stable operation of a larger diameter fan, Rolls-Royce engineers are considering the possibility of using a variable area nozzle. The design of the UltraFan includes the blisk stages of the compressor (Figure 4.18). In addition, the design of the nacelle will allow to reduce the aerodynamic drag.

Further strategic development of the company will be based on Open-Rotor engine technologies.

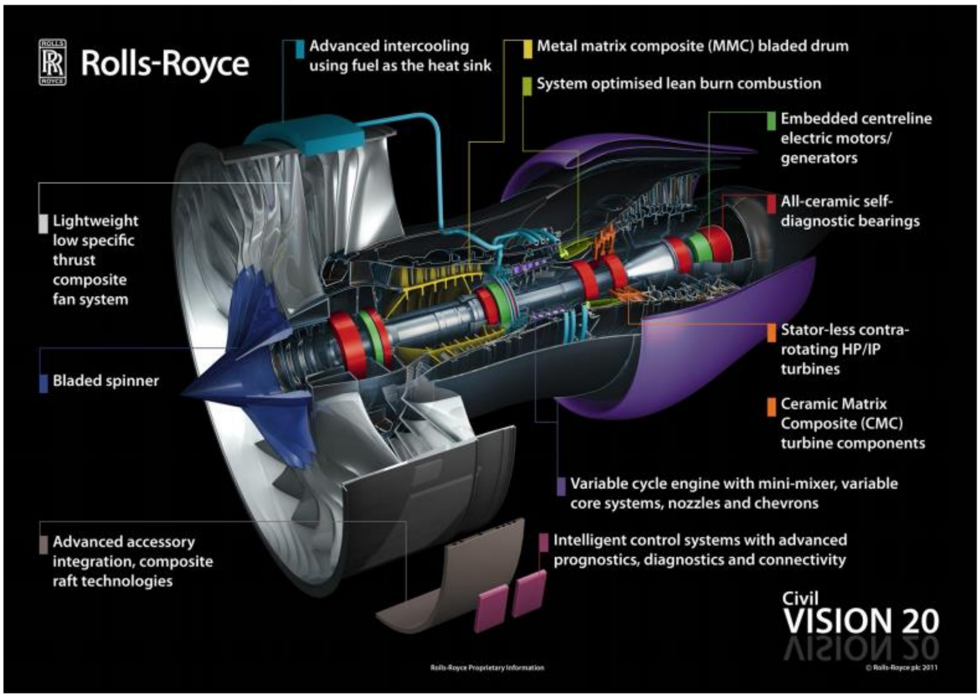


Figure 4.18: Rolls Royce technology for the future engine

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

GE Aviation annually invests more than 1 billion USD in research and development in the aircraft engine industry.

The optimized design of the GEnx engine fan blades and the use of composite materials allow reducing the acoustic emission of the fan. The new GE9X engine is at the R&D stage, including component testing.

The new-generation PASSPORT engine with improved environmental and economic performance is developed for the new Bombardier business aircraft Global 7000 and Global 8000.

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

Effectiveness of advanced technologies to reduce fan noise is verified on model fans, whose diameter is 400-700 mm. TsAGI specialists have experience in aeroacoustic calculations on high-performance multiprocessor complexes

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

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

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

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

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

At this stage, it should also be pointed out that in noise reduction the main expectations are based on benefits associated with ducted turbofans engine concepts. In parallel, Counter Rotating Open Rotor (CROR) engine concepts have re-emerged in recent years as a serious option to provide the needed fuel burn benefits implied by the targets set for aviation CO_2 emissions reduction, noise was considered as a major issue in the initial investigation effort of such engine concept which culminated in a series of noise evaluation flight tests performed in the US in 1986-1987. As a consequence, a significant research effort has been and still is dedicated to noise reduction of CROR engine concepts (Figure 4.19). At this stage, based on results from model tests in an anechoic wind tunnel (TRL 4), CROR powered aircraft with an EIS between 2025 and 2030 can be expected to produce noise levels similar to those of turbofan-powered aircraft currently under development. When placed in perspective with the best expectations resulting from the 1987 post-flight test assessment, this represents a typical 20dB noise reduction on a cumulative basis, a spectacular achievement for the European research effort initiated in 2008. To consolidate such advances, it is important that the effort is maintained through dedicated research aimed at rotor blade aeroacoustics design, engine/airframe installation (Figure 4.20) and flow control techniques in particular. 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.

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

Due to using an improved airframe design in conjunction with a deployable drooped leading edge, elevator displacement and thrust vectoring (see Figure 4.21), for the "Silent Aircraft" developed was a short-length landing flight path with flight-path angle 39°. Upon that the engines are running idle so that to decrease the noise level and to diminish the head resistance, which is required for aircraft holding.

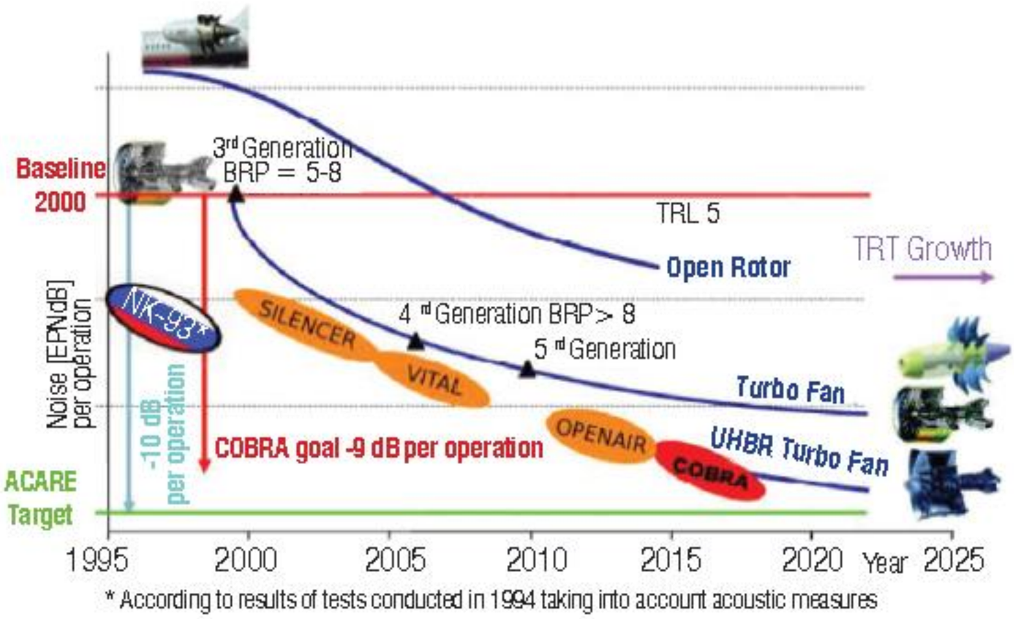


Figure 4.19: Programme Level & EPNL reduction for aircraft noise due to technology improvements

Figure 4.20: Airbus views on a futuristic design for 2030 - future noise reduction technologies with contribution of engine/airframe installation effects

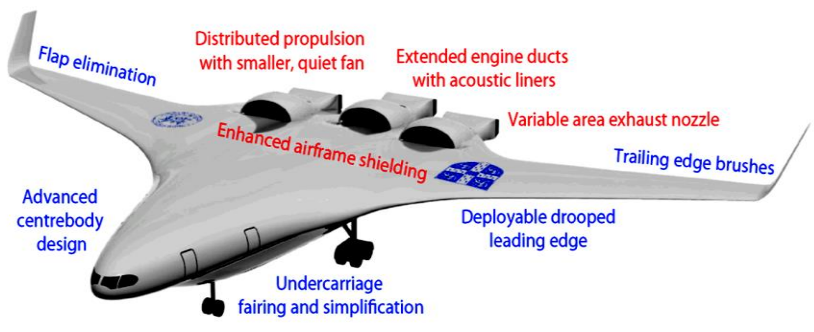


Figure 4.21: Design of Silent Aircraft SAX-40 involving key technologies of noise abatement

Such an approach flight path ensures a peak noise level of 61 dBA outside of the airport perimeter, which is adequate to the background noise level. This procedure would comply with the manoeuvering requirements, but it can affect the runway acceptance rate in the airport if such operations are not separated from the conventional landing approach procedures.

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

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

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

It is obvious that bypass engines with an ultra-high bypass ratio are less noisy than modern engines (Khaletsky, Yu.D. 2014). Contra-rotation open-rotor engines (CROR) - Open Rotor (OR) with pushing propeller can be installed in the rear fuselage of a short- and medium-range aircraft (SMRA). However, the cumulative level of noise generated by them exceeds the level of bypass engines with ultra-high bypass ratio by not less than 15 EPN dB. Fig. 4.22 shows the change in the bypass ratio in the process of the engine's evolution.

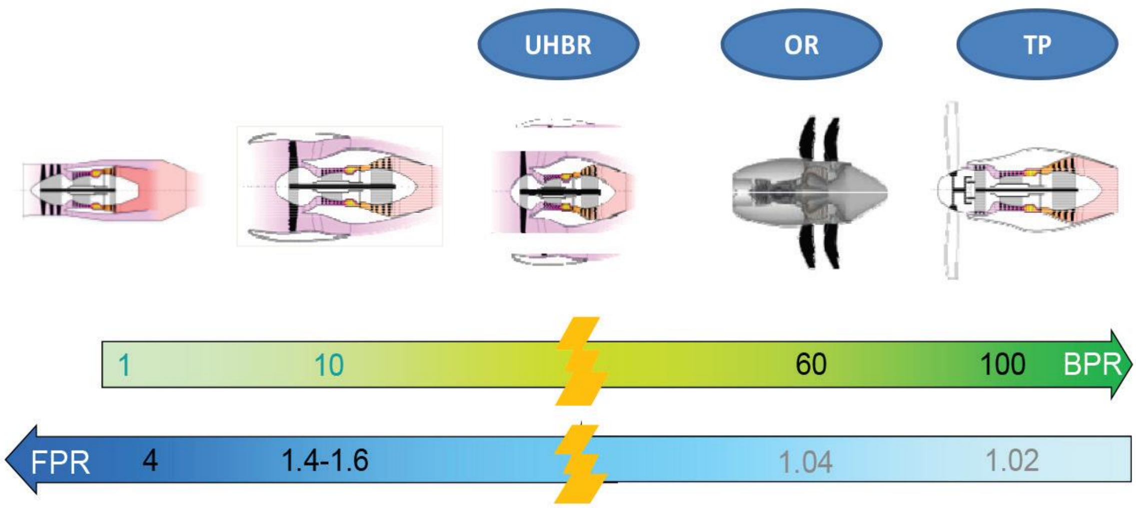


Figure 4.22: Bypass ratio in different engine schemes

[Leylekian, L., Lebrun, M., Lempereur, P. 2014]

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

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

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

The constant stiffening of ICAO standards has contributed to the development of programs aiming at technologies creation for reducing aircraft and engine noise (Figure 3.6-3.8 *their analogues 4.4 and 4.6* in the current report) *[Leylekian, L., Lebrun, M., Lempereur, P. 2014]*.

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

The concept of a low-noise aircraft is considered in the papers [Hileman J.I., et al., 2007; Chevagin, A.F. 2015; Maldar, A., et al., 2008]. The Silent Aircraft Initiative (Figure 4.23) has developed a conceptual design for extremely low noise (61 dB outside the perimeter of the airport during the landing approach) of commercial aircraft using various technical and operational innovations [Hileman J.I., et al., 2007; Chevagin, A.F. 2015; Maldar, A., et al., 2008].

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

Aircraft layouts other than the classic ones are possible, in which the engine's installation losses and the negative aerodynamic interference between the power plant and the airframe do not exceed the level adopted today, but give the background for reducing environmental noise (Figure 3.11) [Chevagin, A.F. 2015].

There are strict limitations on the safety and fuel efficiency conditions for placing the bypass engine on the airframe to implement the effects of engine noise screening. The placement of engines at the top of the wing behind the edge can be taken (for safety and fuel efficiency reasons) for consideration as a way of bypass engine noise screening in the front hemisphere. The jet stream noise screening in the rear hemisphere can be considered only in the dorsal layouts, for which interference losses can be minimized. Bypass engines in overwing layouts tend to dramatically deteriorate the aerodynamic characteristics of the aircraft.

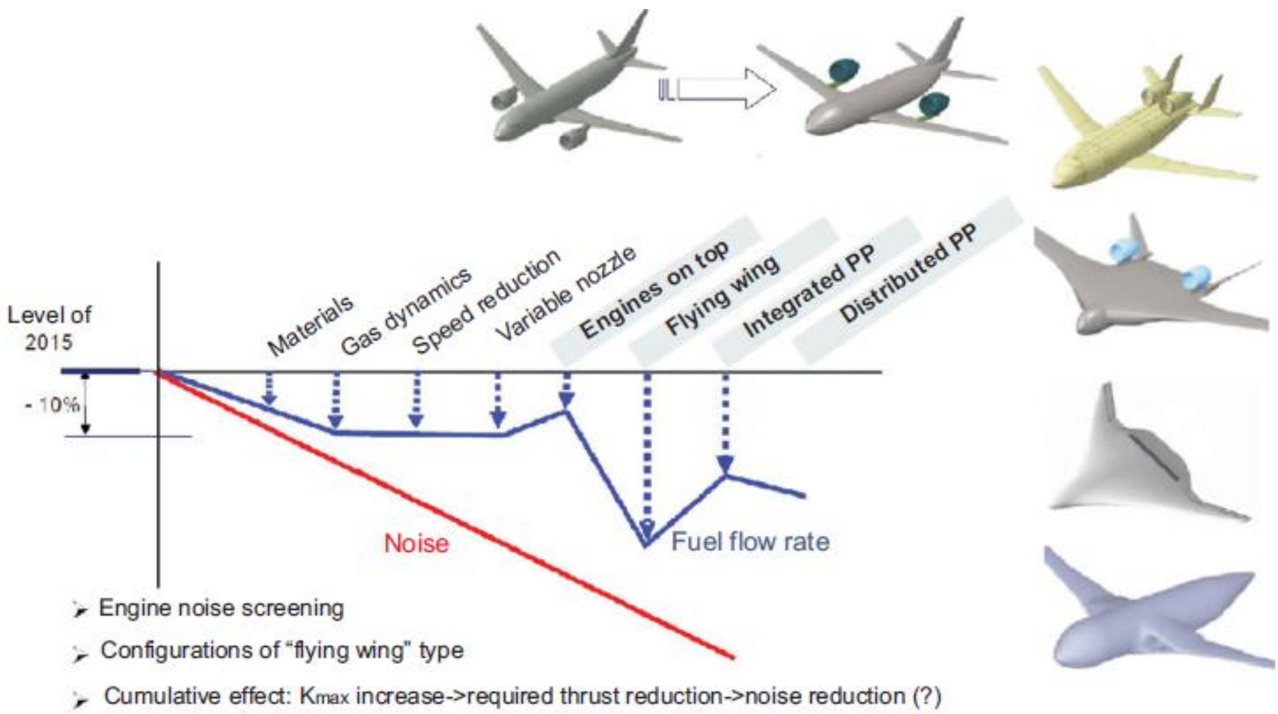


Figure 4.23: Non-standard aircraft layouts

A diversion from the classical layout of the aircraft (Figure 4. 24) is likely to require an increase in the stall margins of the bypass engine in terms of inlet flow nonuniformity at limit conditions of the attack angles and slip of the aircraft.

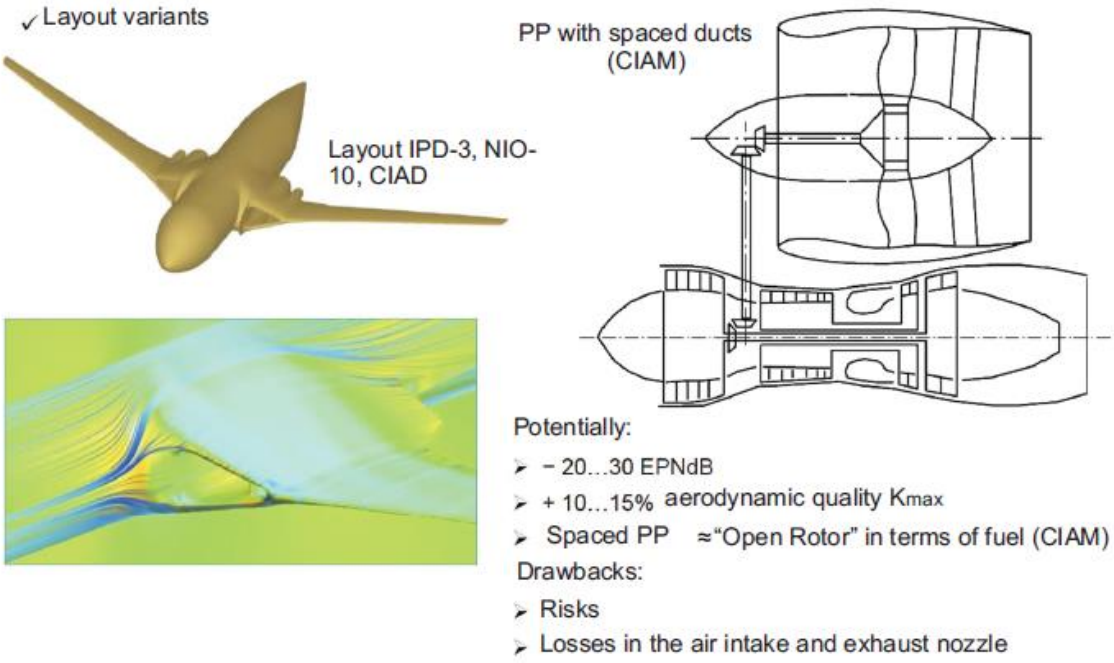


Figure 4.24: Built-in PP layouts with spaced ducts

For the next stage of exploratory studies of non-standard low-noise civil aircraft based on adequate Noise-Efficiency-Safety ratio evaluations, it is necessary to develop the methods of calculating the engine aeroacoustics within the aircraft.

In the paper (Mincu, D.C., Manoha, E. 2014) different methods of acoustic emission calculation are compared when integrating the power plant with the aircraft, 3D models, computational meshes are presented (Figure 4.25). The computational model of the multiply-connected system "engine-attachment-frame" is presented in the paper (Baklanov, V.S. 2010).

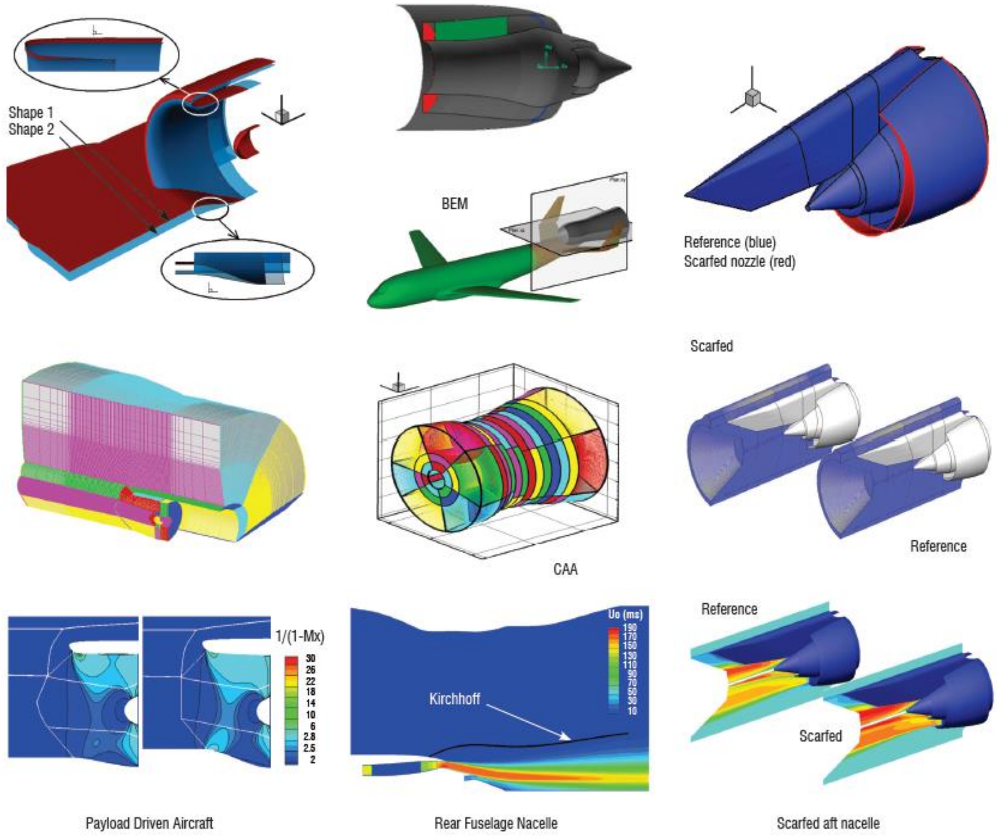


Figure 4.25: Elements of numerical simulation

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

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

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

In the paper *[*Redonnet, S. 2014*]* a hybrid noise prediction method developed in the Onera Research Center, France is considered.

When developing and beta-testing the calculation methods, a very important issue is the availability of an acoustic characteristics database for the aircraft and individual elements.

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

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

In the paper *[*Timushev S.F., Gavriliuk V.N., Aksenov A.A., Klimenko D.V. 2017*]* a new highly effective method is proposed for numerical simulation of three-dimensional tonal acoustic fields at the blade passing frequencies and their higher and combination harmonics generated by an aircraft engine fan. The method is based on a direct solution of the Fourier - transformed wave equation in complex variables considering convection in a rectangular coordinate system with boundary conditions in the form of complex impedance. The noise source can be received by the acoustic-vortex decomposition method.

The paper gives examples of verification and application of the proposed method of sound field simulation considering the boundary conditions in the form of complex acoustic impedance. Good perspectives of its application for the optimization of impeller machines are shown, including to reduce the tonal noise of the bypass engine fans. The LMS software package is well proven in the calculation of acoustic characteristics.

The paper [Piatunin K.R., Arkharova N.V., Remizov A.E. 2014] presents the results of numerical simulation of the fan tonal noise using the LMS Sysnoise software package in the format of Exterior Direct BEM.

The calculations are performed at the approach condition. The calculation results include acoustic emission polar patterns at a distance of 50 m from the engine in the front hemisphere. The simulation was made in a complete setting for all the blade channels of the wheel and the stator blades of the fan stage in the absence of axial symmetry of the stage. The article gives an assessment of the possibility of using the presented approach for analyzing the acoustic characteristics of aircraft engine elements. Also, the manpower input and computational burden required for simulation are presented.

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

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

In order to reduce the noise, researches are being held on the combined silencers of the fan noise, as well as the location of their installation. The results of the research [Khaletsky Yu.D., Shypov R.A. 2010] show that the latticed silencer is broadband and universal. In one way or another, it reduces all noise components practically in the entire frequency range above 1.0 kHz approximately. On average, for four to five discrete components of noise, the sound power reduces for about 4 dB, that is, more than twice.

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

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

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

In the paper *[*Perullo, Ch.A., Tai, J.C.M., Mavris, D.N. 2013*]* the characteristics of an open-rotor engine are analyzed for different operating conditions. Fig. 4.26 shows a comparison of the engines.

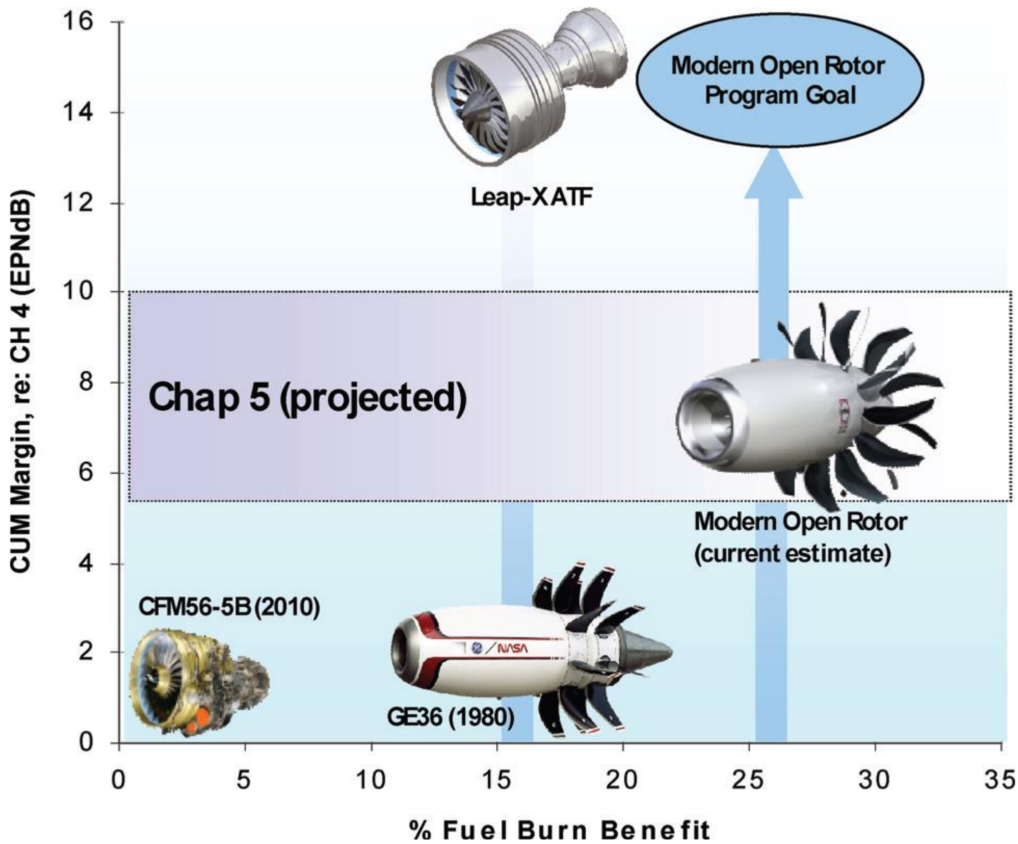


Figure 4.26: Advantages of an open-rotor engine

The calculation of the characteristics of an open-rotor engine is presented in the paper [Hendricks, E.S., Tong, M.T. 2012]. It is shown that the designed engine will have higher efficiency. It is also noted that such engines have a margin of 13 dB according to ICAO requirements (Chapter 4). To improve the acoustic characteristics of an open rotor, reliable methods of noise calculation are needed.

In the paper [Farassat, F., Dunn, M.H., Tinetti, A.F., Nark, D.M. 2009] methods for predicting open-rotor noise available at NASA Langley are discussed. Three codes called ASSPIN (Advanced Subsonic-Supersonic Propeller Induced Noise), FW-H_{pds} (Ffowcs Williams-Hawkings with permeable data surface) and FSC (Fast Scattering Code) are compared. The first two codes are in the time area, and the third code is the frequency area code. The capabilities of these codes and the requirements for input data are presented, as well as the output data. In addition, the authors proposed procedures for further improvement of these codes. In particular, a method based on equivalent sources is described to eliminate false signals in the FW-H_{pds} code.

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

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

The paper [Sgadlev, V.V. 2009] presents the results of the blades number optimization for the stage of one of the contra-rotation fans, developed under the European program VITAL. In addition, the paper presents a method for evaluating the acoustic characteristics of a fan. The method is based on obtaining analytical solutions of the Tyler-Sofrin theory and the theory of disturbance propagation in a duct. A program has been developed to obtain these solutions and to present them in a user-friendly form.

After optimizing the number of blades of the contra-rotation fan stage, the number of modes decreased by 38.5%, which implies a corresponding reduction in noise levels. This technique will be more efficient if it incorporates the weight coefficients of the mode for better consideration of the human hearing physiology and for more optimal adjustment of the sound-absorbing structures (SAS) characteristics.

The results of the paper [Danner, F., Kendall-Torry, C. 2014] showed that when the diameter of the second wheel of an open rotor is reduced by 20%, acoustic emission from the interaction between the first and second rotor wheels are reduced.

The jet stream is one of the main sources of the jet engine noise, therefore, research on reducing the jet stream noise is still of vital importance. In the medium term, a method of reducing the jet noise for the engines with m=7...9 is the use of a chevron or splined device for the nozzles of the bypass and core ducts.

The effectiveness of this method makes up 0.5 EPN dB at take-off (average certification value for takeoff run and climb) [Solonin V.I., KhaletskyYu.D. 2010]. An effective way to reduce the noise of a jet stream is to increase the bypass ratio. According to rough estimates, using a 3dB/m dependence, a power plant with a bypass ratio of m≈12 will reduce the noise level of the aircraft at control points by 9 EPN dB. **Table. 3.5** shows the methods for reducing the noise of the jet stream in the medium term [Solonin V.I., KhaletskyYu.D. 2010].

The paper [Rybinskaya, L.A., Bul'bovich, R.V., Kychkin, V.I. 2017] provides an overview of methods for reducing jet noise. In various research programs, advanced methods for reducing the noise of a jet stream are investigated. These methods include liquid injection, the use of a bevelled nozzle, the use of micro-jets, high-frequency excitation. All of these methods have a potential noise reduction of 1-2 EPN dB for takeoff run and climb [Rybinskaya, L.A., Bul'bovich, R.V., Kychkin, V.I. 2017; Solonin V.I., KhaletskyYu.D. 2010].

In order to reduce the jet stream noise, an analysis of known results of experimental studies for 5 researches was made using correlation method to identify the jet stream noise sources in the paper [Panda, J. 2005].

In the paper [Medviediev, V.V., Timko, O.S. 2012] a comparative analysis of methods for reducing the noise of an aircraft engine exhaust jet was made. It is shown that mixing the flows is practically the only way to improve the acoustic characteristics of the engine without deterioration of its economy.

At high values of the bypass ratio (m>6...8), the positive effect of mixing on the economy is negligible and does not justify the increase in the mass of the engine due to the mixing chamber, but the acoustic effect remains. Therefore, for the engines with m<6, the use of a mixing chamber gives the best results, both in the economy and in acoustics. In addition, in such a scheme of the engine, acoustic processing of the nozzle walls and screening of the bypass duct with the mixer is possible, which allows reducing the fan noise emitted to the rear hemisphere, and screening of the core duct with the mixer and the decrease in the average rate of flow from the nozzle due to mixing reduces the noise of the turbine and the jet stream itself. These measures are implemented on the PS-90A2 engine.

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

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

The introduction of the presented measures in the power plants with m <8 will allow reducing the total noise level of the jet stream at the control points, in the nearest decade it will be about 1.0-3.0 EPN dB. By increasing the bypass ratio the jet stream noise decreases due to the decrease of its velocity, which is estimated at 3-4 EPN dB at the points of takeoff run and climb [Solonin V.I., KhaletskyYu.D. 2010].

Currently, the contribution of the core duct noise into the total noise of the aircraft at certified points is much lower than the noise of the fan, jet stream and airframe. Nevertheless, with an increase in the bypass ratio of the engines and the introduction of effective methods for reducing the noise of the fan, the jet stream and the airframe, an increase in the share of the core duct is expected. The sources of the core duct noise are the turbine, the combustor, the bleed valve and the compressor [Solonin V.I., KhaletskyYu.D. 2010].

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

In the paper [Serrano, A., Fernández, J.R. 2014] the modal characteristic of a low-pressure turbine is investigated. As a result of the research, a radial structure of modal noise during rotation is obtained, which makes it possible to study in more detail the mechanism of noise generation at a supersonic flow in a turbine. The data processing in the evaluation of acoustic power is described in details. Acoustic characteristics were measured with a special device that rotated with the NMM turbine.

High-temperature noise silencers (composite sound-absorbing structures), lining of the nacelle mixing chamber are used for acoustic efficiency of the core duct. For the reduction of the combustion chamber noise, studies are being conducted aimed at research on the noise sources in the combustion chamber and the mechanism for generating acoustic emission.

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

A promising method of reducing the turbine noise is the acoustic lining of its flow section above the wheel [Solonin V.I., KhaletskyYu.D., 2010]. The effectiveness of the method has been verified for a fan [KhaletskyYu.D., Shypov R.A., 2010].

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

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

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

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

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

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

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

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

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

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

When reducing the engine noise, acoustic optimization of the nacelle takes an important place. Application of seamless SAS, bevelled air intake will reduce the suction noise by 1-4 dB. The use of active-passive SAS can reduce the tonal noise by 2-7 dB.

The use of a chevron or splined device in the nozzles of the bypass or core duct of aircraft powered by bypass engines with a bypass ratio of m = 4 ... 6 will reduce the jet stream noise by 1-3 EPN dB.

The reduction of the jet stream noise during take-off for the engines with a bypass ratio of m = 7 ... 9 due to the use of a chevron or splined device for the nozzles of the bypass and core ducts makes up 0.5 EPN dB. With an increase in the bypass ratio, the effect of the chevron nozzles is decreased, and therefore the investigation of various methods for reducing the jet stream noise plays an important role.

The use of micro-jets, whose influence is based on the aerodynamic interaction between the peripheral jets and the main one, can reduce the low-frequency noise by 1-2 dB, while the thrust value remains the same.

Plasmatic actuators can reduce the jet by an average of 1.3 dB, their designs are simple, as they are integrated into the surface and do not have moving parts.

A multi-tube nozzle provides a decrease in the total acoustic power of the flow by an average of 8 dB, while the part of low-frequency components decreases and the noise spectrum shifts to a higher frequency sector when compared with a round nozzle due to an increase in the surface of the jets mixing with the environment in the area near to the nozzle exit area.

The use of mesh screens reduces the total acoustic power of the flow by an average of 5 dB, leads to a decrease in the share of low-frequency components and an increase in the share of high-frequency noise components. The effectiveness of mesh screens increases in combination with other methods of noise reduction, for example, SAS (Figure 4.27). Screening the jet stream noise with a secondary gas flow can lead to a noise reduction of up to 5-7 dB in the high-frequency area of the acoustic spectrum.

An ejector noise-suppression nozzle with a multi-element outlet leads to the disappearance of discrete components in the jet stream spectrum (Figure 4.28), while the noise of the jet stream decreases by an average of 10 dB. However, a significant disadvantage is weight gain, reaching 6%.

The use of acoustic influence is difficult in practice due to the complexity of the application, but this method allows reducing the noise level of the jet stream by 2-3 dB. Screening of jet stream noise, based on the phenomenon of acoustic waves diffraction, allows reducing the noise level up to 3.5 dB.

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

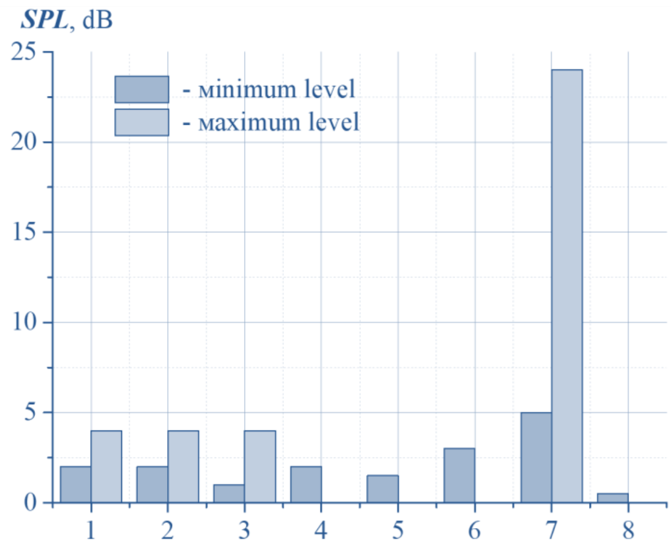


Figure 4.27: Effectiveness of methods for reducing the noise level in the fan: In Figure the numbers indicate the positions: 1 - sweep of the rotor wheel blades; 2 - sweep and inclination of the fan stator blades; 3 - optimization of the rotor wheel circumferential speed; 4 – variable-area fan nozzle; 5 – stator blades with SAS; 6 – rotor wheel with noise silencer; 7 – rotor wheel and stator blades with active influence; 8 - hubless fan

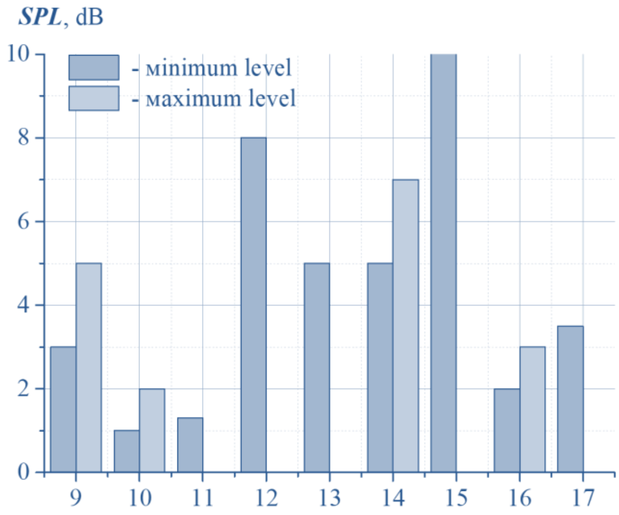


Figure 4.28: Effectiveness of methods for reducing the level of jet stream noise: In Figure the numbers indicate the positions: 9 - chevron nozzle; 10 - microjets; 11 - plasmatic actuators; 12 - multitubular nozzle; 13 - mesh screen; 14 - screening of jet stream noise by secondary gas flow; 15 - ejector noise-suppression nozzle with a multi-element outlet; 16 - acoustic impact; 17 - noise screening

4.1.2 Aerodynamic Noise and Operating Procedures

The progress in the reduction of engine noise implies that: (i) it remains the dominant noise source at take-off and with cut-back in climb; (ii) on approach to land, with the engine at idle, the aerodynamic noise can predominate. Thus overall noise reduction at airports requires consideration of not one but two classes of noise sources;

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

- Aerodynamic 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 4.29). 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 a corresponding change of the aircraft structure, as described in [Dobrzynski W. M].

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.

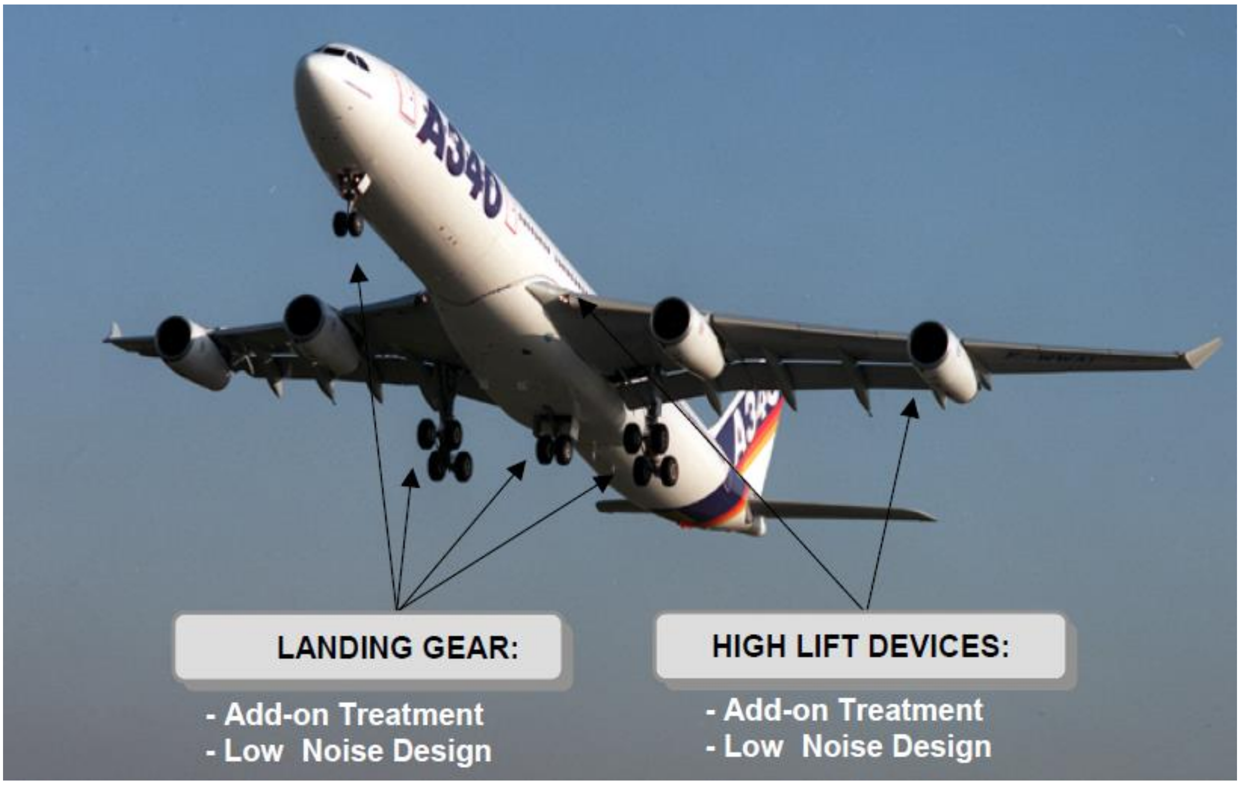


Figure 4.29: Airframe noise reduction technologies

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 were assessed during EU Silence(R) project for their possible contribution to ACARE 2020 goal (Figure 4.30):

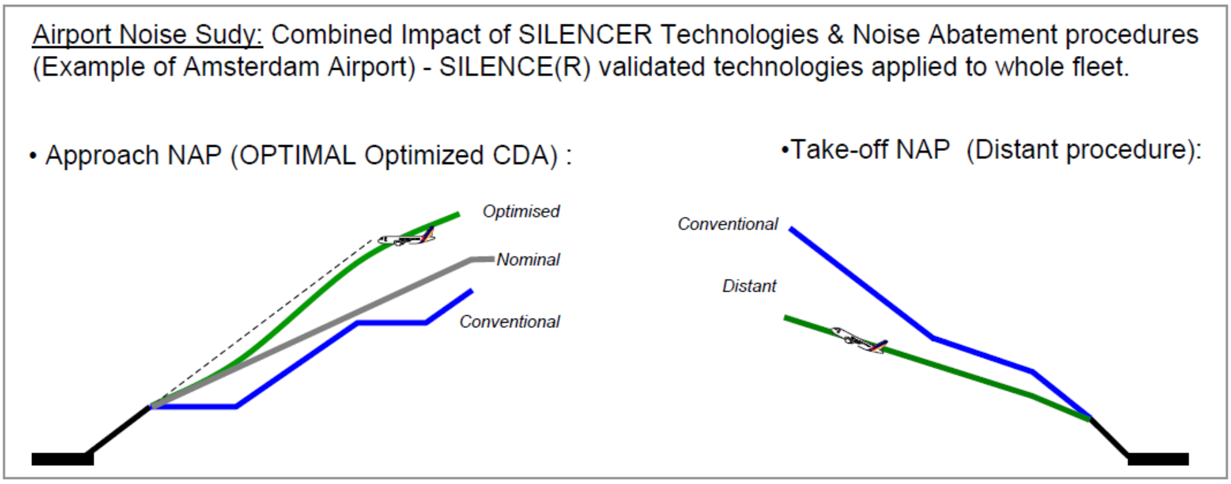


Figure 4.30: Departure and approach noise abatement procedures

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 of fuel savings per landing; and

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

The magnitude and scope of the reductions, as well as the specific procedures to be used to achieve them, should be determined through a comprehensive noise study. The study should also include an analysis of emissions impacts and fuel burn, as these variables may be affected by procedure changes both in the air and on the ground. The aircraft operators and ANSP should be parties to the study to ensure the safety and feasibility of the procedures and to take advantage of their technical expertise. The environmental benefits of some operational procedures are straightforward and easy to visualize preferential runways or flight tracks move aircraft away from more noise-sensitive locations. Conversely, the benefits assessments for NADP's and CDA procedures are extremely complex and may require detailed modelling to be well understood. It is imperative that accurate aircraft operating data and specific operator flight procedures are applied as input to the noise and emissions models and that impacts on airport and airspace capacity be analysed. It is worth repeating that some noise abatement operational procedures may increase emissions or derogate airport capacity while providing significant noise relief. Appropriate consideration of all potential environmental impacts is essential, particularly as priorities change and procedures evolve or come up for review.

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

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

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

- Improve and continuously update the understanding of how noise from air transport operations affects people, with a significant focus on the influence of non-acoustic factors. Figure 4.31 provides a rough survey of the most important non-acoustic variables for long-term annoyance and annoyance at night.
- Provide technical support for the successful implementation of planning policies compatible with traffic growth for the long-term benefit of the communities. This will require specific thematic research aimed at better integration of land use planning (LUP) in decision making.

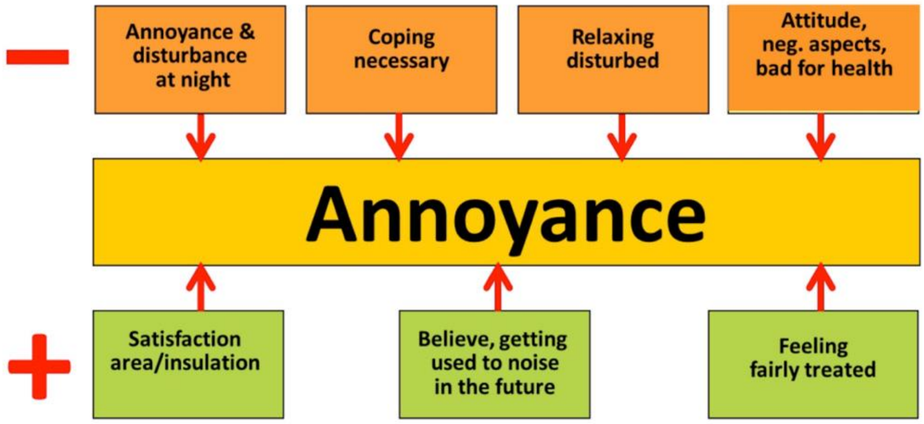


Figure 4.31: Overview of most important non-acoustic factors contributing to aircraft noise annoyance [Collin D]

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 NO_x

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

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

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

Figure 4.32 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-LyeR].

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

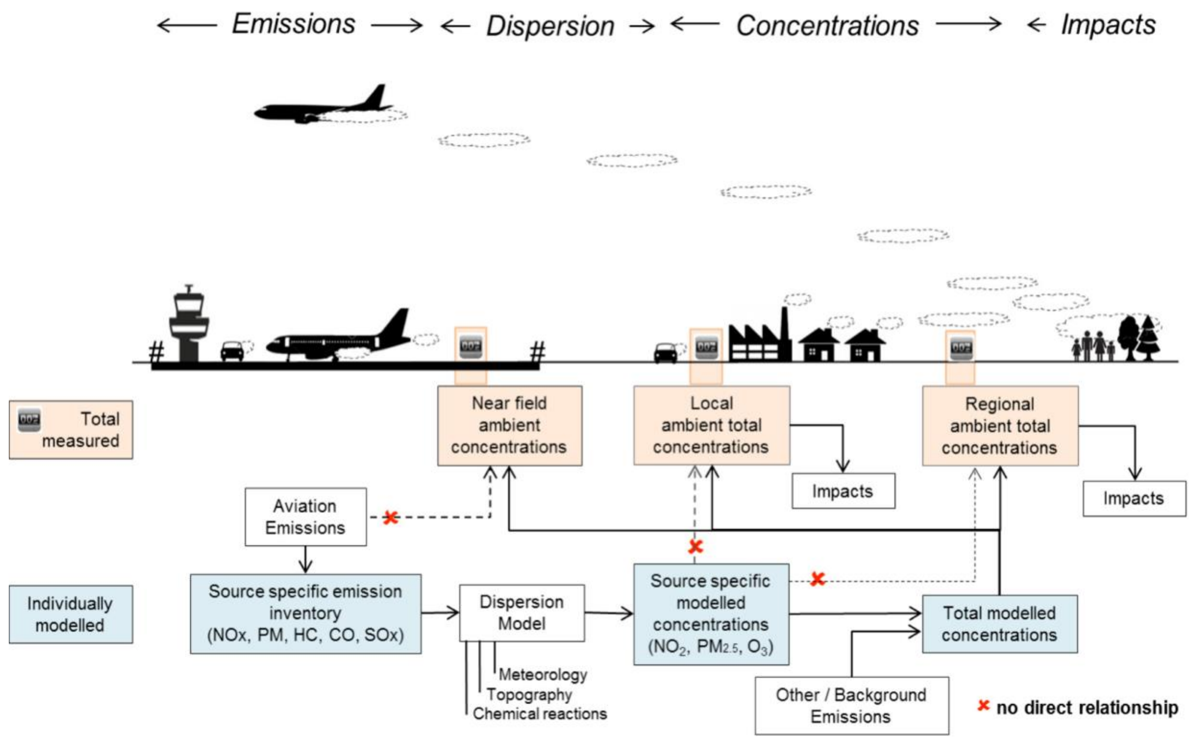


Figure 4.32: Schematic presentation of emissions, dispersion, concentrations and impacts with their interaction at airport level [Miake-Lye R]

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

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

Air vehicle emissions depended on the following factors: number and type of airplanes, types of air engines, fuel used, time spent for each phase of operation, flight power and distance [Song, S.-K., Shon, Z.-H., 2012]. Traditionally researches of air vehicle emissions and their effects can be mainly divided into two parts: emissions of pollutants to atmosphere taking place within LTO phase (local pollutant emissions) and flight phases not related to LTO (i.e. 915 m and at cruise condition level) (ICAO), Doc. 9889, 2011). Aircraft emission effect on human activity at ground level was the most important and all the actions coincided with the airport as for emission sources grew rapidly [Tsilingiridis, G., 2009]. Therefore, there were reviewed air vehicle emissions within LTO phase except for the cruise condition phase. In the emission cadaster, there were applied detailed data on activity provided by ZBAA, including each type of air vehicle, origin and destination point, estimated time of arrival and the actual time of arrival, estimated time of departure and actual time of departure. In this research, the authors used not only improved models to calculate the time of climb and descent, but also the actual time of aircraft taxiing using the information received from the airport (Table 4.4).

In Table 4.4 there are shown emissions of NO_x, CO, VOC_s, SO_2, and $PM_{2.5}$ for the main engines of air vehicles, APU, ground support equipment (GSE), ground access vehicles (GAV), private transport, stationary sources, airport oil depot in 2015. APU emissions are shown in Table 4.5.

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

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

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

Table 4.4: Emissions in Beijing airport

Table 2 – Emission factors of auxiliary power units.

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

APU: Auxiliary Power Unit.

Table 4.5: APU emissions

In Figure 4.33 there are shown contributions of various emission sources in ZBAA. It's obvious that air vehicle emissions are the most important of all sources an airport, of them, the annual CO, VOC_s, SO_2, and $PM_{2.5}$ made $7{,}56\times10^3$, $3{,}49\times10^3$, $3{,}66\times10^2$, $4{,}6\times10^2$ and $7{,}15\times10^1$ tons per year.

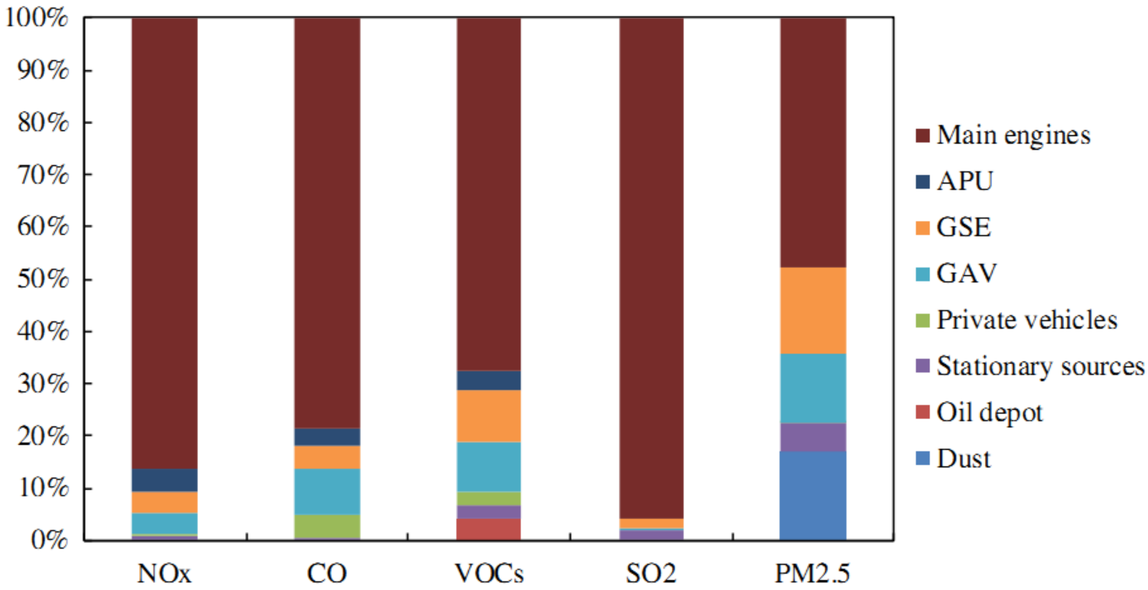


Figure 4.33: Contribution of pollution sources in emissions in international airport Beijing in 2015

The aircraft was the main airport sources, of them emissions NO_x, CO, VOCs, SO_2 and $PM_{2.5}$ made 86,3 %, 78,7 %, 67,4 %, 95,6 % and 48,0 % of the total emission volume respectively. From the review of air vehicle emission characteristic, it was revealed that NO_x mainly is released at takeoff and climb stages that make 20,5% and 55% of the total emission volume (Table 4.6).

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

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

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

Table 4.6: Comparative data on emissions in big airports of the world

Taxiing of air vehicles is a considerable source of COи SO_2 emissions, their share makes 91,6 % and 92,2 % of the total emission volume. The mixing level is higher in summer; therefore, emissions of pollutants in air were at the highest level throughout the year. The ratio of NO_x, CO, HC, SO_2 and $PM_{2.5}$

from air vehicles made 27,2 %, 25,7 %, 25,5 %, 26,9 % and 27,0 % of annual emissions respectively [He, J.-C., and Y.-Q. Xu, 2012].

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

CO_2 emissions from air vehicles had been low in China till the year 1980, while in 1960-1979 they had made 328×10^3 t at average. Starting from the 1980's especially after 1990s CO_2 emissions had been rapidly growing (Fig. 4.34). The average growth of CO_2 emissions for air vehicles in China made 826×10^3 tons per year.

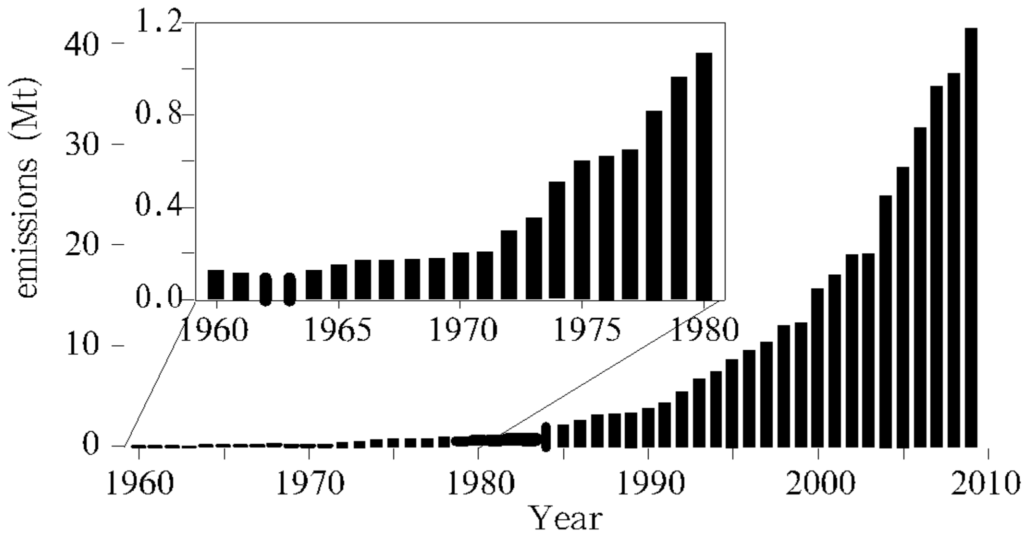


Fig. 4.34: Annual CO_2 emissions from civil air vehicles in China within the period 1960-2009

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

Some of the gaps for the production of airport emission inventories are displayed in the Table 4.7:

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 4.7: 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 the previous Table there is still a lot for improvement in airport emission inventory making, and that further consolidation is needed in the knowledge of airport emissions sources and their activity (performance), emission factor and calculation algorithm. Linked to both inventory making and air quality modelling, there is a need for further development and validation of performance-based emissions modelling, and the need for harmonisation in this area.

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

In order to improve fuel efficiency, engine pressures and temperatures are increased with time which can lead to higher 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 turbojet 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 policymakers with a view of what technology could be expected to deliver emission reductions in the future. The first of these reviews was to focus on NO_x and to help achieve this, a panel of Independent Experts (IEs) was appointed and tasked with:

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

The goals can be seen in Figure 4.35, which is taken from the 2006 report of the IEs, together with goals proposed by the EU ACARE and the US Ultra-Efficient Engine Technology (UEET). It is important to note that these other goals were not used to influence the CAEP goals and were plotted simply for comparison. The graph also illustrates the historic ICAO NO_x Standards and highlights the large gap between the goals and the latest standard. It is important to note that the goals indicate that significant NO_x reductions are achievable over the 10 and 20-year timescales based on the leading edge of control technologies; while standards, on the other hand, are based on already certified technology.

Figure 4.35 also illustrates the continuous improvement achieved over time with newly certified engines achieving the largest margin to the limits. Some of the engines certified since 2008 are already close to mid-term and long-term technology goals. Figure 4.36 illustrates the evolution of the average margin to the CAEP/6 NO_X limit for EASA certified in-production engine models. During the last five years, the margin has increased by approximately 3% per year. It is noted however that the trend is influenced by which engines go out of production, and whether the new entries in the ICAO Aircraft Engine Emissions Databank represent new engines or derived versions of existing engines with smaller evolutionary improvements.

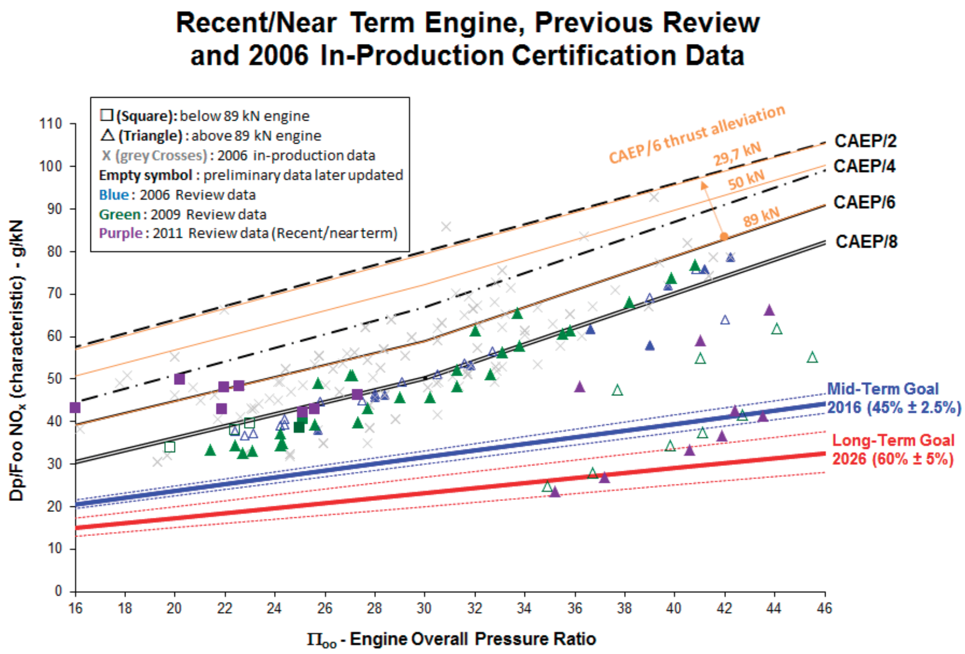


Figure 4.35: Historical ICAO certification Standards together with the 2006 MT & LT goals.

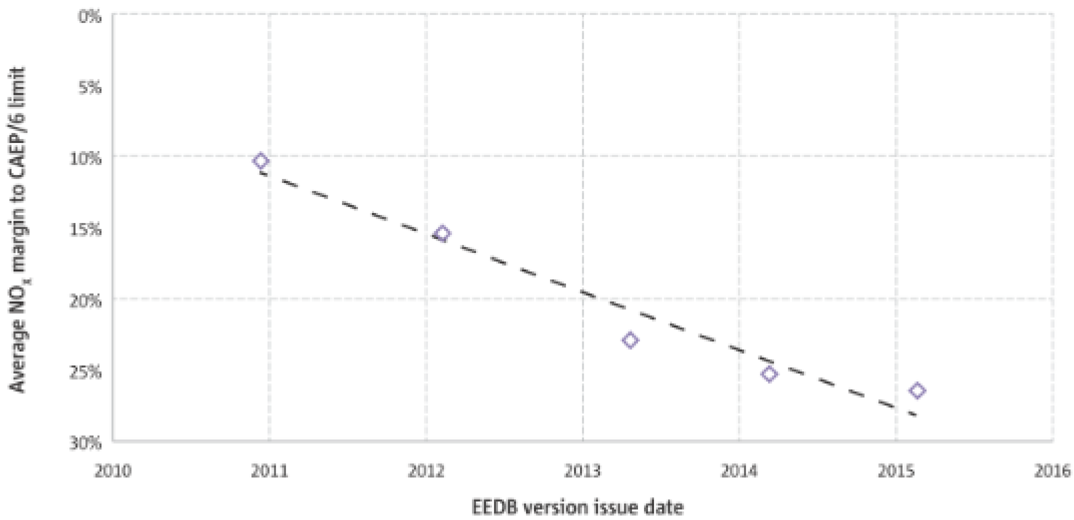


Figure 4.36: Improving average NOx margin to CAEP/6 limit for in-production engines shown in successive versions of the ICAO EEDB

Figure 4.36 uses the recognized NO_x certification metrics and shows the amount of NO_x produced from an LTO cycle (Figure 4.37) on the vertical axis (grams per kN of thrust), and the engine overall pressure ratio (OPR) at the take-off condition on the horizontal axis. It is evident that the larger, higher thrust engines operating at higher pressure ratios, and consequently at higher thermal efficiencies, produce greater amounts of NO_x. In relation to the degree of uncertainty, it should be noted that the bandwidth was greater for a longer time period. The medium-term (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.

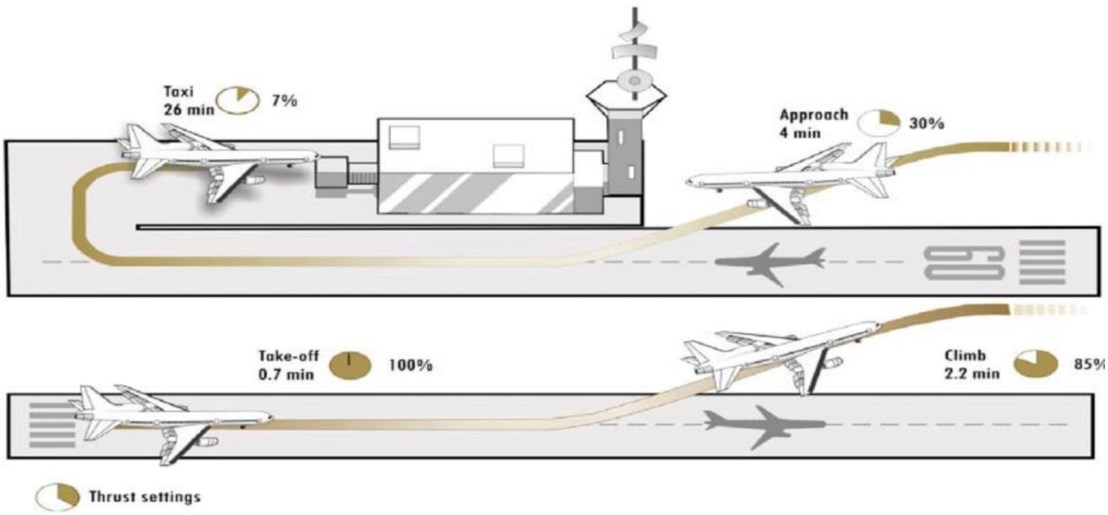


Figure 4.37: Illustration of ICAO emissions certification procedure in the LTO cycle.

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 the impact of aircraft NO_x on both surface air quality and global climate change was, if anything, more compelling than during the first review. Nevertheless, given the still considerable uncertainty about the quantification of these impacts, the IEs recommended continued research on NO_x emissions, and other emerging concerns such as particulate matter (PM), and the role of NO_x in PM formation. As in the 2006 report, it was again concluded that for SAQ, NO_x continues to be an important pollutant and in the context of Global Climate Change (GCC) its ranking versus CO_2 continues to depend crucially on the length of the time horizon. It appears that NO_x is more important in shorter time periods, with CO_2 dominating in the longer term, and then continuing to do so over many hundreds of years.

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

The Figure 4.38 provides a summary presentation of the test data results received for this review with the two types of combustor identified separately; the data points coloured grey being for RQL combustors and those in red being for the new staged-DLI combustors. As with the first review, the conclusion reached was that RQL combustors appear likely to meet the MT goal, though a significant challenge remains, the LT goal may not be achievable particularly for high OPR engines. Dramatic reductions in NO_x production from the use of new generation staged DLI combustors were in line with the expectations recorded in the 2006 Report, although the migration towards the LT goal was not expected so soon. However, the widespread of NO_x performance raised questions about how such families of engines might be handled in the future within a goal setting process.

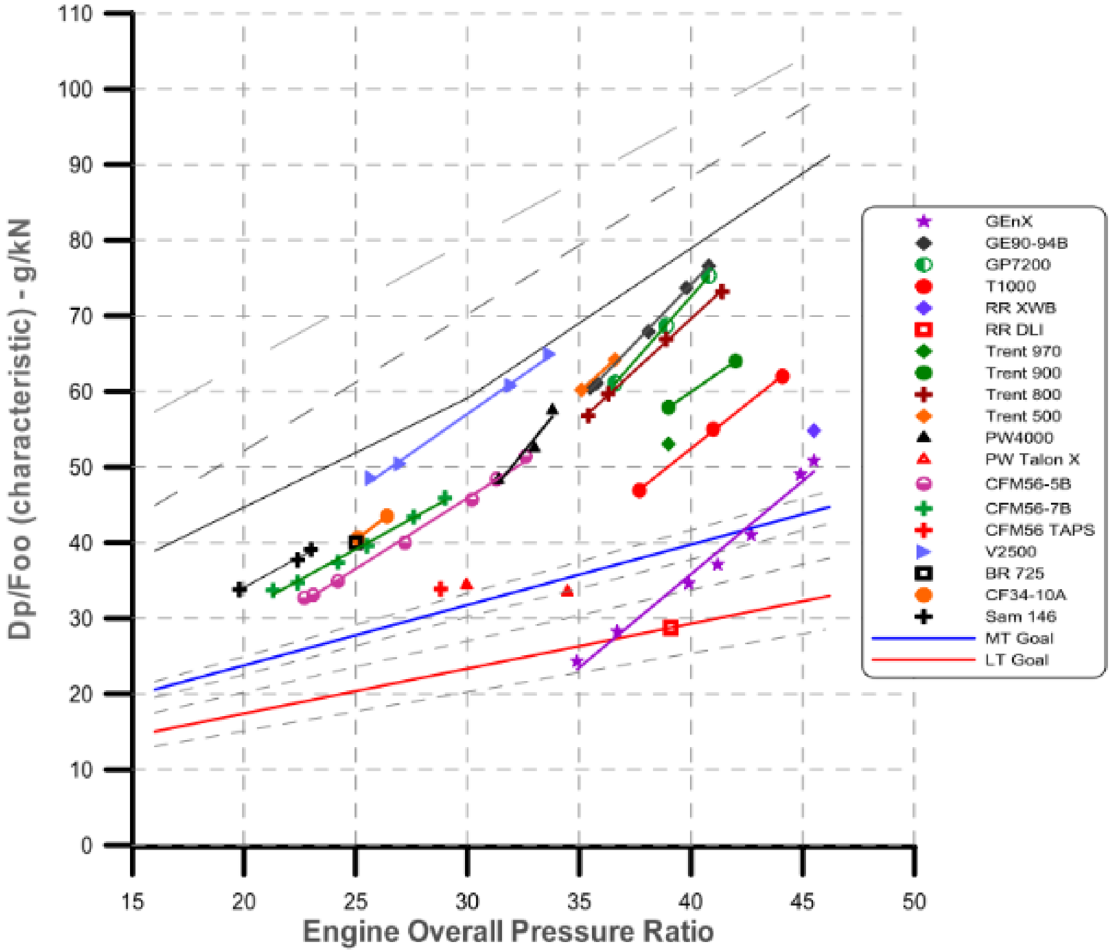


Figure 4.38: 2009 Review data with RQL combustors in grey and new mid-OPR engines. Generation staged DLI combustors in red. Note these data points area mixture of certificated engines and high TRL developments

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

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

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

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

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

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

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

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

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

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

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

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

Demonstrator Open Rotor (Fig. 4.39) designed in the framework of immense research programme Clean Sky in Europe is a strategic direction of SAFRAN RESEARCH&TECHNOLOGY efforts and is a key part of SAFRAN plans on the design of the power plant meeting future needs of aircraft manufacturers till the year 2030.

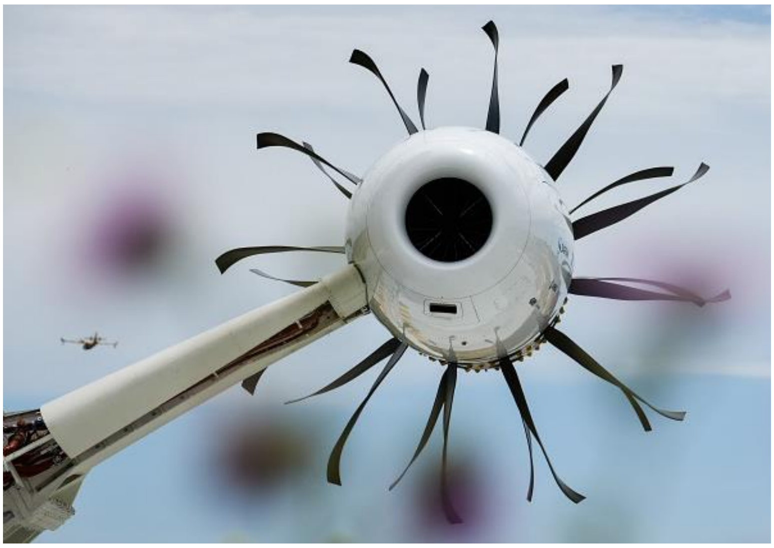


Figure 4.39: Demonstrator SAFRAN "open rotor"

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

NASA project "Environmentally Responsible Aviation" (ERA) with industry involvement develops technologies of fuel combustion for low-emission combustion chambers of the new generation to meet the requirements of the target level 2020. Prospective combustion chambers will reduce emissions of nitrogen oxide (NO_x) by more than half from the emission level of the existing combustion chambers reducing simultaneously the noise level and specific fuel consumption. In 2012 at NASA ASCR test bench there were determined emission characteristics of two technologies of fuel combustion - PW ACS and GE TAPS. The measurement results showed a considerable reduction of NO_x emissions by 75% lower than CAEP 6 2004 level [Chang CT, Lee CM, Herbon JT, Kramer SK, 2013].

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

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

Starting from the traditional design Twin Annular Premixing Swirler (TAPS) made with the employment of several technological and commercial programmes including GEnx and LEAP (Fig. 4.40), GE company has extended possibilities of that technology to reach the aims of N+2 generation on NO_x and efficiency. Architecture, scale and cycle of the engine were set using the review of engine-aircraft system pointing at the concept of aircraft and engine Hybrid Wing Body (HWB), which might meet the key aims of the generation as for NO_x level, specific fuel consumption and noise reduction. The main concept of GE combustion chamber design of N+2 generation is an increase in air share employed for preliminary agitation in the combustor flame tube head (higher 70%). Moreover, there are employed structural elements, which improve heat-air mixability. Increase in air volume for preliminary agitation can lead to a breakdown of difficulties coincided with either provision of serviceability (combustion efficiency and combustion stability) or structural durability (due to reduction of cooling air consumption).

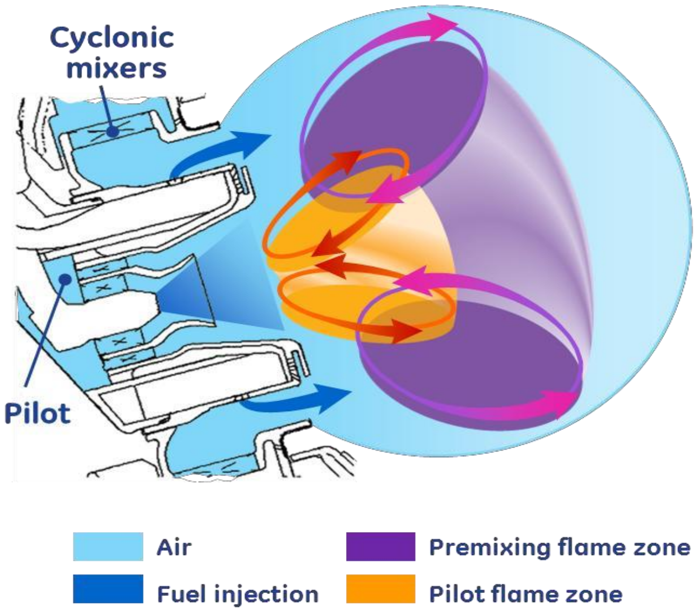


Figure 4.40: Concept of TAPS dilution section

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

On the basis of result review of emission characteristic experimental determination 3 most prospective versions (of 13 versions under research) were selected and then further design optimization was made, after that one final structural version of the combustion chamber was tested by NASA new five-head section (Fig. 4.41) [Herbon J., et al., 2017].

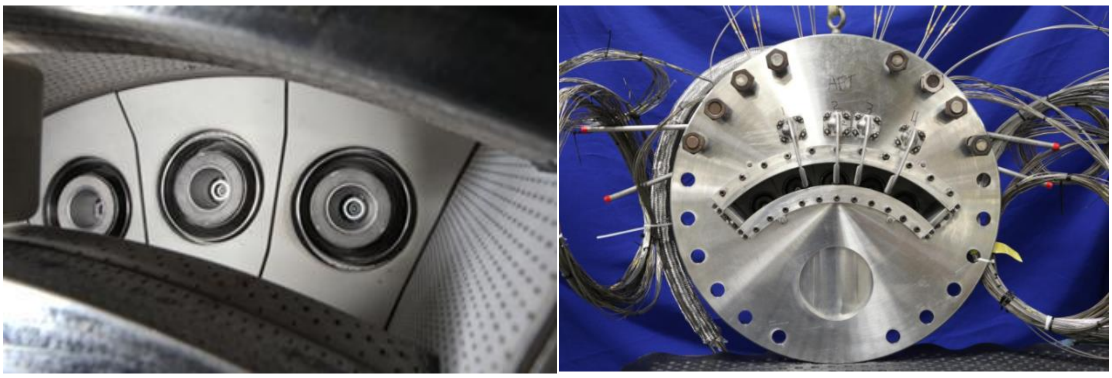


Figure 4.41: Combustion chamber 5-sectional sector

By results of NO_x emission level experimental determination in 5-head section the GE combustion chamber provides the level meeting 19% NO_x from CAEP6 regulatory requirements at target level for the engines of N+2 generation meeting 25% from CAEP6 regulatory requirements at good combustion efficiency and acceptable level of pressure fluctuations at this design stage (Table 2.2).

Further development of that technology will be focused upon the thermal state, mechanical strength, processibility and design optimization in order to find a compromise between the provision of fuel combustion efficiency and pressure fluctuation level in the combustion chamber from one side and NO_x emission level per LTO cycle.

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

Table 4.8: NO_x emission level of GE 5-head section for ICAO LTO cycle

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

P&W company in the framework of the EA project has demonstrated several very diverse concepts including also the improved version of its TALON X combustion chamber with rich combustion. Final conception version on Axially Controlled Stoichiometry (ACS) of the combustion chamber was selected for NASA tests that considerably improved its characteristics compared to those achieved two decades ago. ACS concept was preliminary tested in three-sectional sector at UTRC installation, then it passed NASA tests at ASCR object (Fig. 4.42).

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

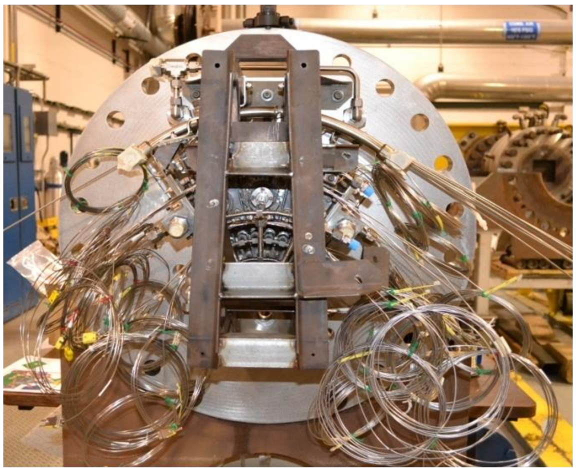


Figure 4.42: Three-sectional sector of low-emission combustion chamber at NASA ASCR bench (Pratt & Whitney)

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

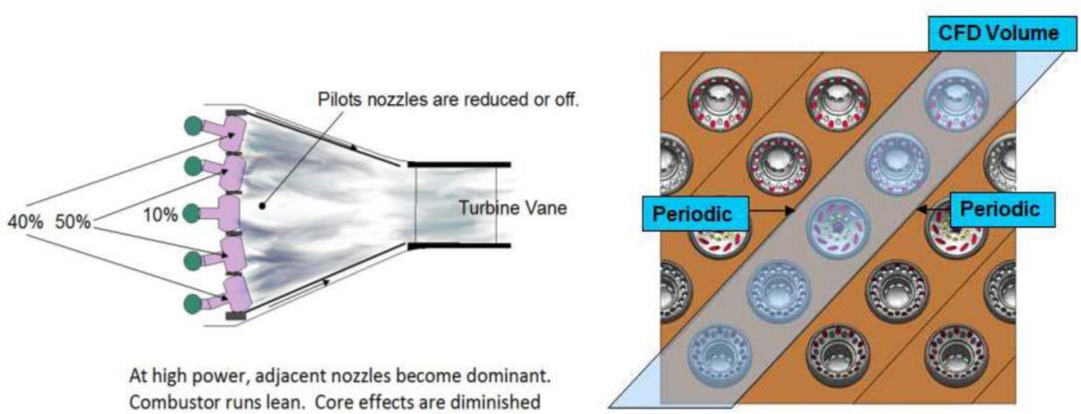
Both combustion chamber concepts from GE and P&W have surpassed the target level for engines of N+2 generation meeting the level 25% from the allowance of CAEP-6 LTO NO_x at good combustion efficiency and pressure fluctuation at level TRL 4. Both combustion chamber conceptions researched to meet the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

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

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

Goodrich (at present called UTC Aerospace Systems) has developed a modular LDI array around discrete-jet based air-blast fuel nozzles (Fig. 4.43a). Intense mix turbulence level is produced close to the fuel injection point. As a result, it is obtained rapid breakup of fuel and vaporization sheet accelerating the process of homogeneous combustible mixture formation especially, at low engine power setting.

Rows of slightly recessed pilot nozzles, designed to ensure secure ignition, are dispensed in the multiple-stage matrix (Fig. 4.43). Air flows through the pilot nozzles makes 10% of the total air consumption and fuel is dosed independently of the supply to the major elements. It is anticipated that employment of separately prepared areas of the fuel-air mixture will permit them to minimize NO_x emissions thus providing a wide range of combustion chamber steady operation.



a) b)

Fig. 4.43: Goodrich multi-zone multi-stage LDI concept

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

Woodward FST based their developed concept on combined types of fuel nozzles by the simple vortex and shear action. Their LDI package module consists of multi-stage series of smaller and more compact nozzles surrounding the central bigger module, which provides low-power operations. Modules can be added together as a multi-component sector (Fig. 4.44). The built-in module provides a zoned effect and shields from its neighbours. At low power settings, the fuel-air mix distributed uniformly can be excessively lean to burn.

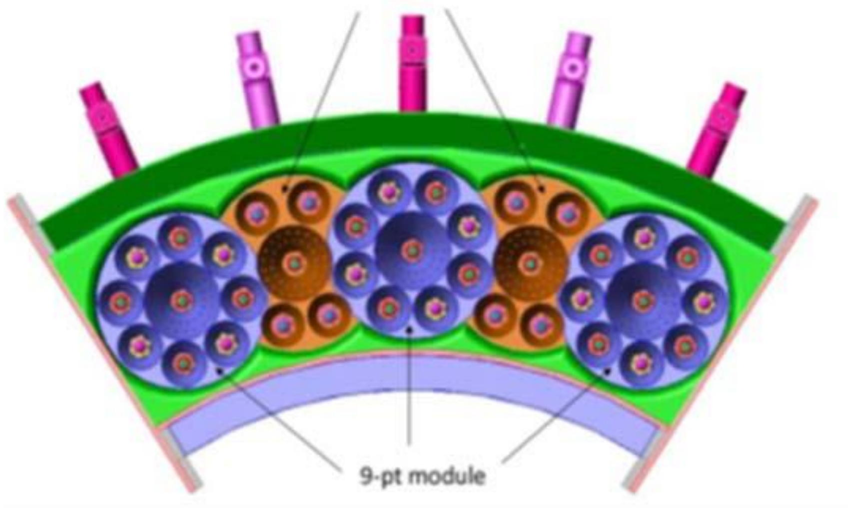


Figure 4.44: Woodward LDI package in 5-sectional sector

As a result, it is used a multi-stage fuel-feeding scheme to ensure the combustive composition of the mixture at very low total equivalence numbers. In Figure 4.45 it is shown 5-burner annular compartment during the test to determine the margin for a lean blowout. At present, the works on the maturation of the fuel preparation system are underway **[**Lee, Ph., 2012**].**

Parker presented the version of multi-stage 3-zone injector module designed under UEET NASA programme. The concept originated from the idea of updating CC modern injectors applying new equipment having the improved characteristics (Fig. 4.46). The module is composed of miniature mixing cups each fueled by a pressure-swirl nozzle. The cups are formed using Parker's platelet technology and produce intense turbulence when the fuel injection takes place. Three zones are formed by canting the side nozzles away from the middle layer to provide some relief from injector interaction. Multiple fuel stages are used to shift fuel spatially to provide the leanest and acceptably-stable burnable fuel-air mixture (Fig. 4.47). This package passed tests at middle power conditions and is accepted for testing under high pressure in NASA [Lee, C-M., Chang, C., Kramer, S., and Herbon, J. , 2013]

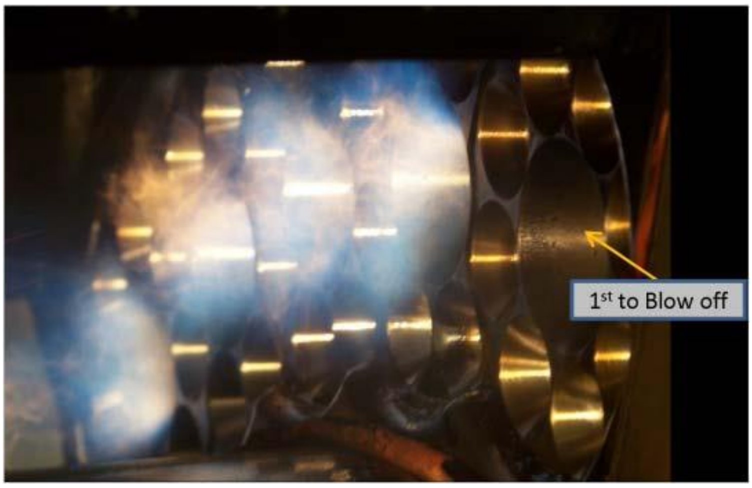


Figure 4.45: LDI Woodward package undergoes tests with lean mixture

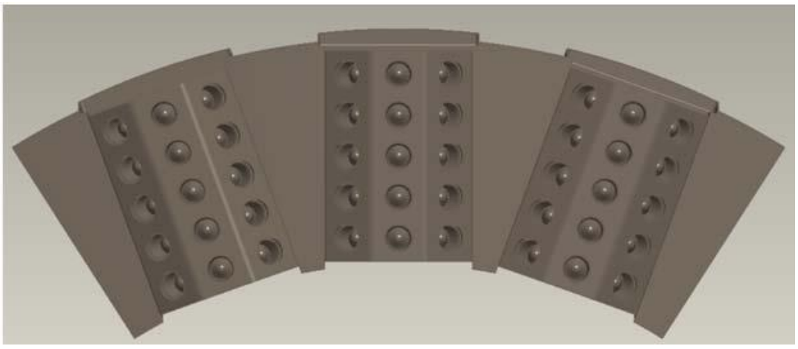


Figure 4.46: Conceptual implementation of 3-zone module

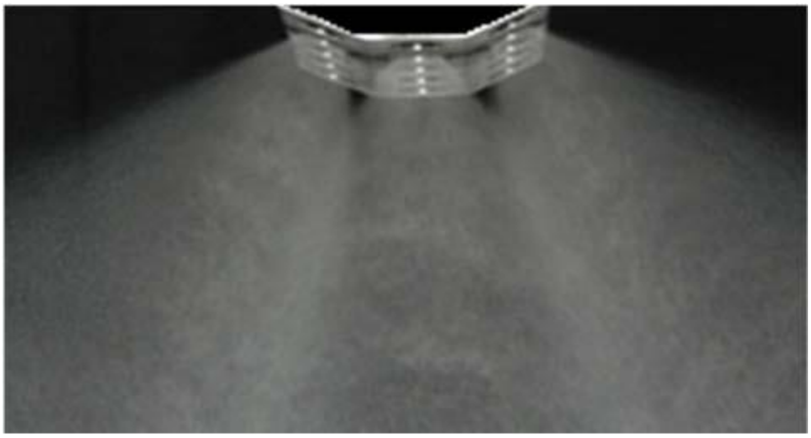


Figure 4.47: Spray test using Parker 3-zone probe

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

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

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

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

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

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

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

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

- increase HPC gas-dynamic stability margin;

- curtail operating costs.

In the bypass turbojet Trent 1000 due to the fluid drive coupling applied in intermediate pressure power off-take at engine starting by the starter, both rotors – middle pressure spool and HPC are spun with the result that the starting time is shorter than 40 s [*Aviation Week, 8/V, 2006, v. 164, №19, p.48-50*]. At flight conditions, the power off-take for the generator drive is made mechanically from the middle-pressure shaft. Generators of each engine can produce up to 0,5 MW of electric power for B787 electrical systems.

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

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

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

Besides in the work [Ninian, D.; Dakka, S.M., 2017] the wings for morphing were designed – innovative technology, which has potential to improve aerodynamic efficiency (feature) and reduction in aircraft noise patterns. This research was focused on the reduction of induced drag caused by lifting force on the flaps of the airfoil section and improvement of the design to reach aerodynamic efficiency (Table

4.9). Modelling has shown almost 11% growth of the lift factor for the initial morphing wing and 15,4% for the optimized morphing wing compared to the traditional wing layout. At angles of attack 0, 5, 10 and 15 degrees the optimized wing has the gain in aerodynamic efficiency by 18,3 %, 10,5 %, 10,6 % and 4 % respectively compared to the common wing. Modelling also showed that there is considerable improvement of pressure distribution at a lower surface of the wing with morphing. An increase in the flow smoothness and decrease in vortex dimension along the wing trailing edge led to drag reduction. It was observed also pressure rise on the lower surface. The morphing ring reduced the vortex dimension; therefore, the noise levels measured were reduced by 50%.

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

Table 4.9: Noise level of traditional and adaptive (morphing) wings in the air tunnel

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

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

1. Aircraft weight reduction.
2. Improvement on the aerodynamics of aircraft to reduce aerodynamic drag.

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

The weight reduction of aircraft was achieved through the introduction of light advanced alloys and composite materials, new designs for aviation systems, improved and new production processes. For example, the Boeing 787 entered service in 2011 and has an airframe made up of almost 50% carbon fiber reinforced plastic and other composites, offering an average weight reduction of 20% compared to similar traditional aluminium structures. Just as an example of the introduction of new technologies aimed at reducing fuel consumption and reducing emissions of pollutants, the scheme of the Airbus A350XWBis presented (Figure 4.48). The future volume of aircraft emissions will be determined by the intensity of air traffic, air traffic control, new aviation technologies and the speed of change in the fleet of aircraft.

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

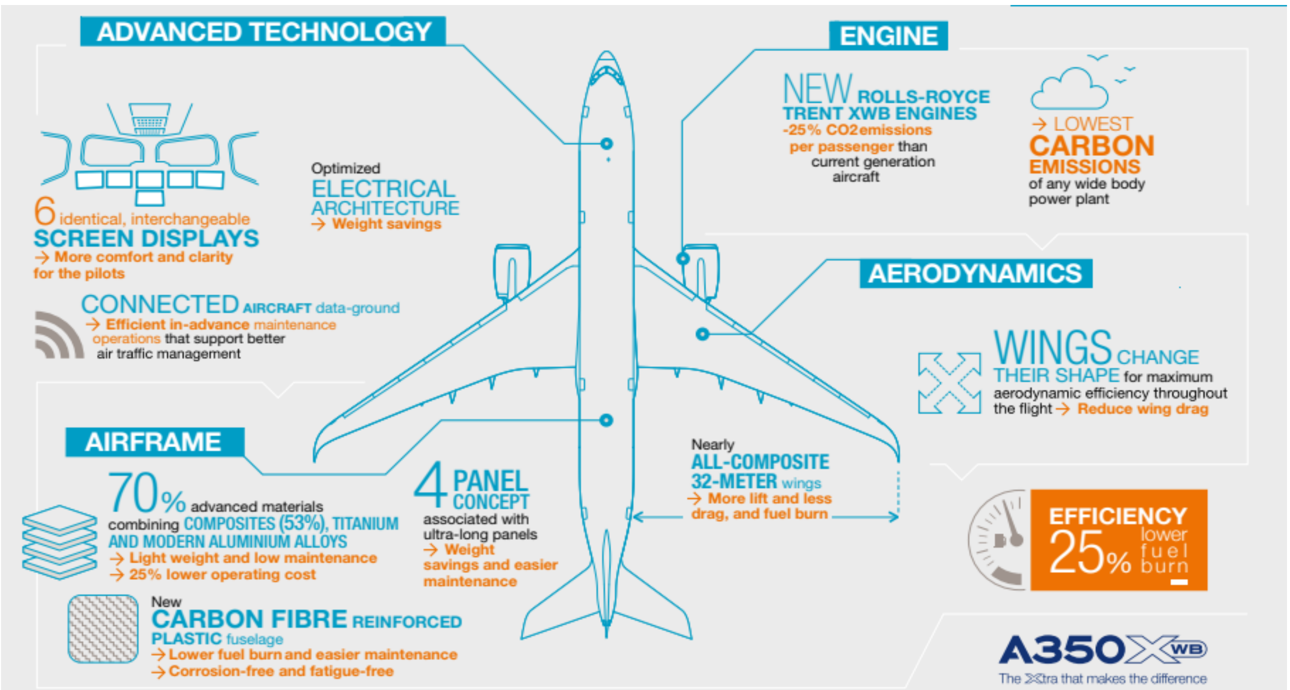


Figure 4.48: Advanced Airbus Technologies

As can be seen in Figure 4.49, CO_2 emissions follow the same tendency as air transportation from 1990 to 2014. CO_2 emissions increased by 80%, remaining stable between 2005 and 2014. However, it is expected that they will also increase by 45% more between 2014 and 2035. Nitrous Oxide emissions doubled between 1990 and 2014, but it is expected, that technological developments speed will grow at a faster rate than in previous years and are expected to increase by 43% between 2014 and 2035, considering the prediction for air traffic growth (Figure 4.50)

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

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

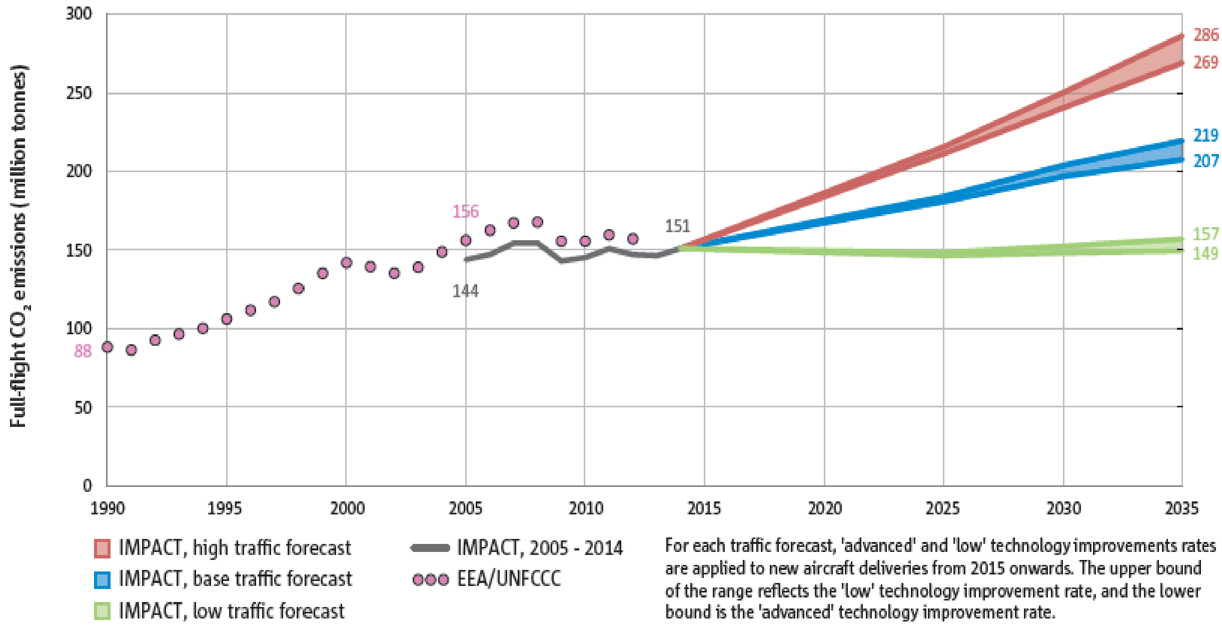


Figure 4.49: CO_2 emissions with prediction after 2014 considering different scenarios

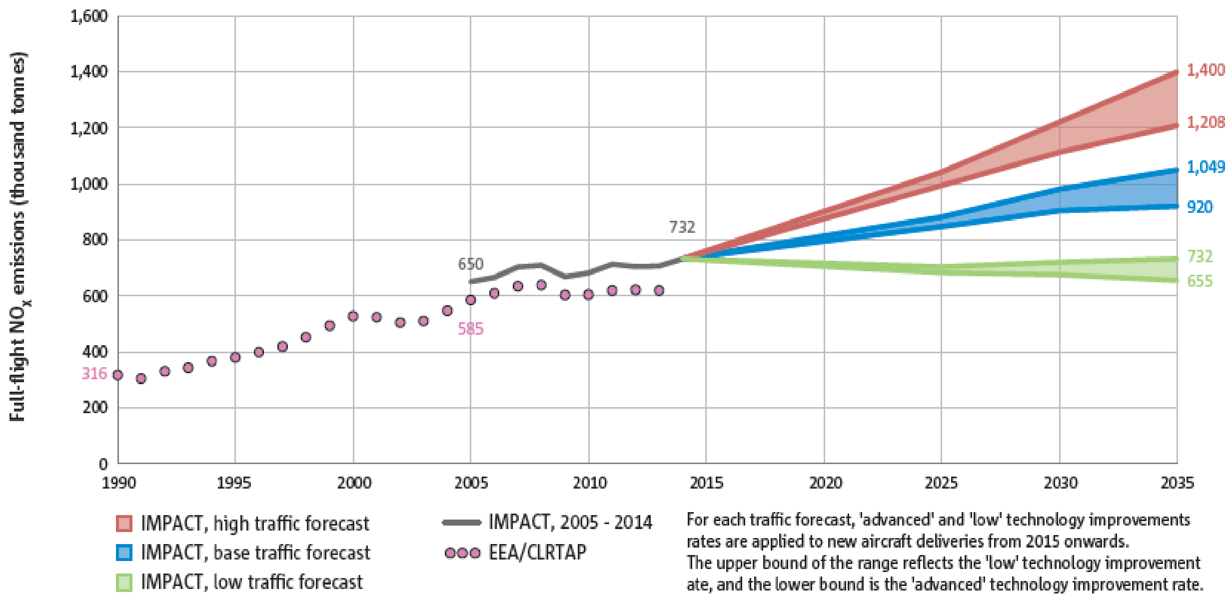


Figure 4.50: NO_x emissions with predictions after 2014 considering different scenarios

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

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

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

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

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

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

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

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

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

The recommended CO_2 Standard has been developed at the aeroplane level and therefore has considered all technologies associated with the aeroplane design (e.g. propulsion, aerodynamics and structures). Once adopted by the ICAO Council, the Aeroplane CO_2 Emissions Certification Standard will be published as a new Annex 16, Volume III. The framework for the CO_2 Standard consists of a certification requirement and regulatory limit, as shown in Figure 4.51, and the work to develop the CO_2 Standard was divided into two phases. Phase 1, which was completed at the ninth meeting of the CAEP (CAEP/9) in February 2013, resulted in the approval of some of the details regarding the applicability of the Standard, the CO_2 Metric System and the development of a CO_2 Standard certification requirement. Phase 2 involved the development of the regulatory limit lines and the applicability requirements such as scope and date.

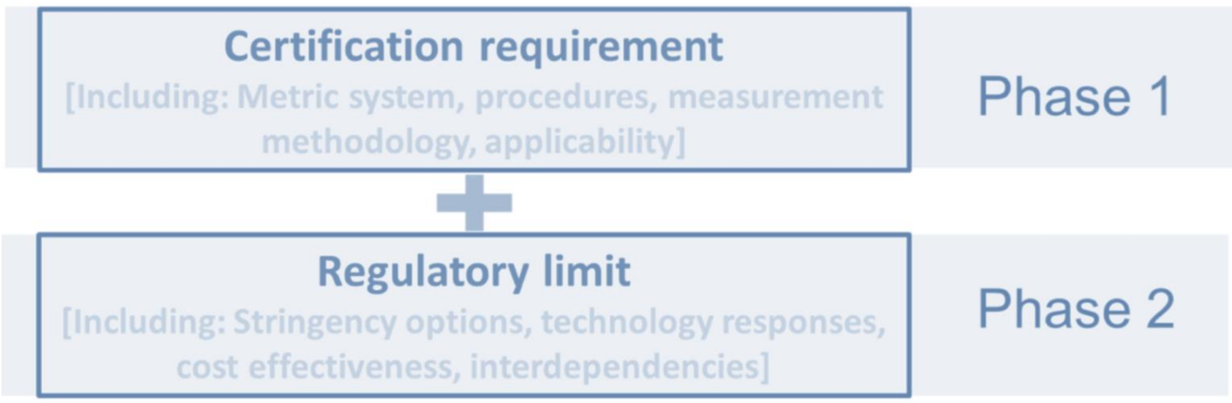


Figure 4.51: The framework and development phases of the CO_2 Standard

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

The recommendation on the CO_2 emissions standard was supported by a significant data-driven process and the cost-benefit modelling analysis of several different CO_2 stringency options. The new CO_2 emissions Standard is recommended as being included in an entirely new Volume to Annex 16 (Volume III). Figure 4.52 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 an additional margin for a sector. This is particularly recognised for aeroplanes of MTOMs less than 60 tonnes and with fewer than 19 seats maximum passenger seating capacity, where for new aeroplane type designs the applicability date of the standard is 2023.

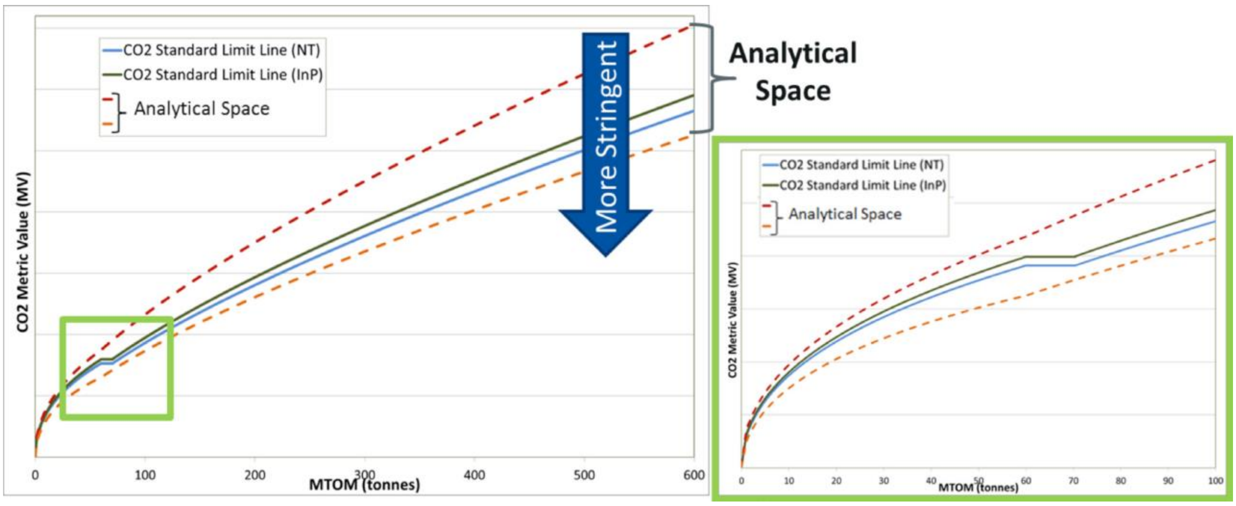


Figure 4.52: The CO_2 Standard regulatory limits for the aircraft

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.

Figure 4.53 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.

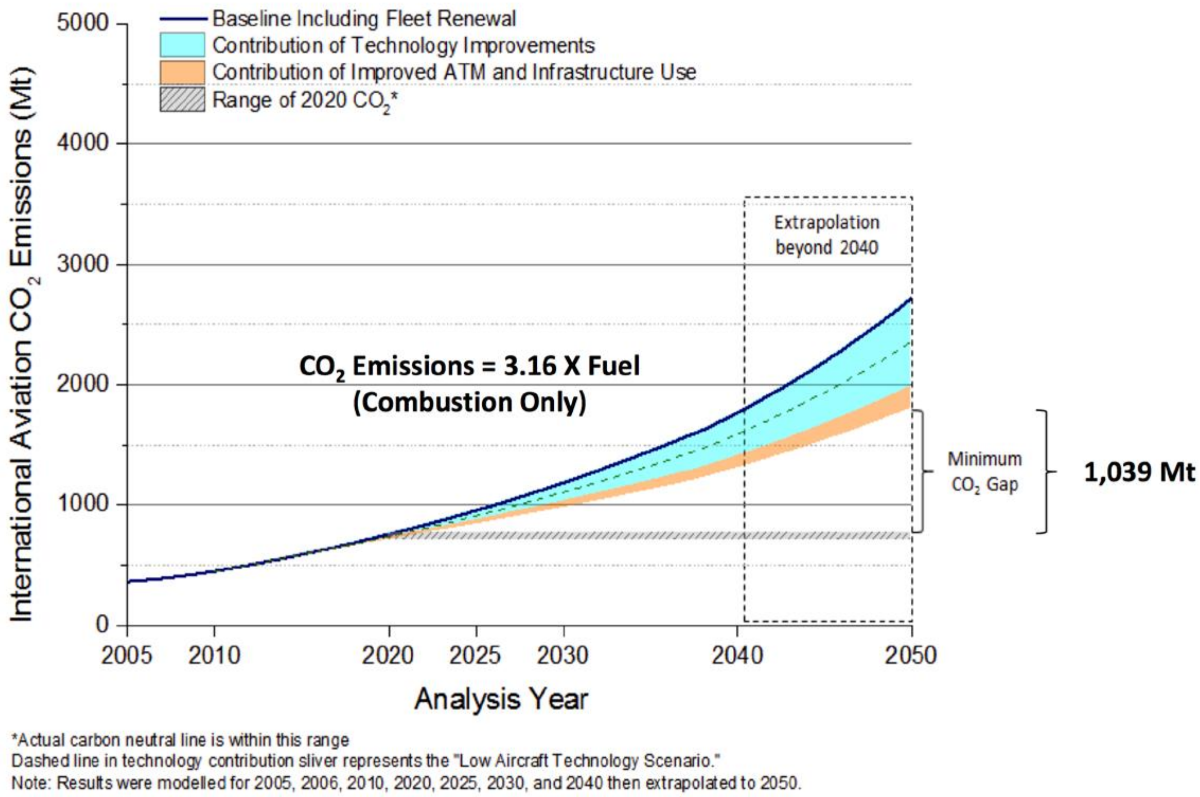


Figure 4.53: CO_2 Emissions Trends from International Aviation, 2005 to 2050

Figure 4.54 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 Figure4.20 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 Figures 4.53 and 4.54 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 4.55 [Nickol, C., Haller, W., 2016] shows us existing and promising NASA aircraft to reach the goals.

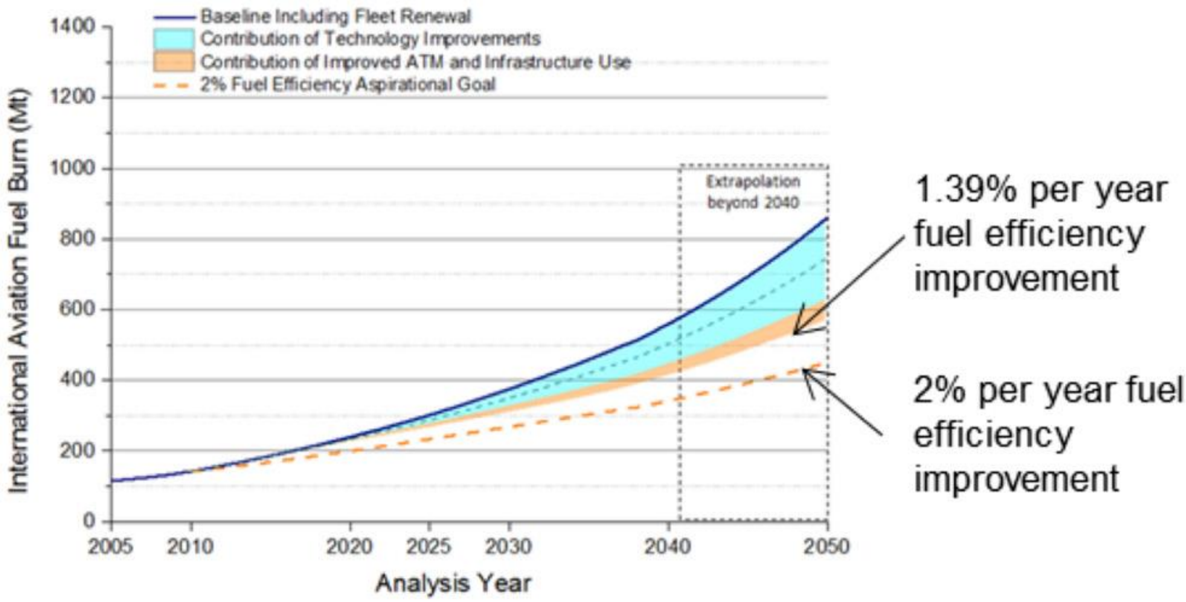
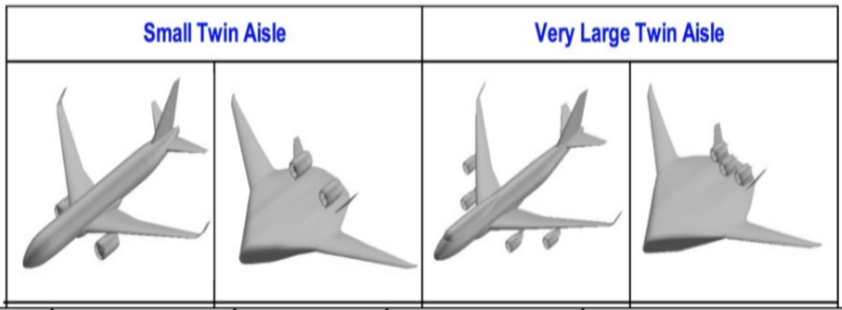


Figure 4.54: Fuel Burn Trends from International Aviation, 2005 to 2050



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

Figure 4.55: NASA N+2 aircraft generation

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

Scenario 1 is an alternative to "do nothing" without N + 1 and N + 2 aircraft types entered into the structure. The purpose of the baseline scenario is to understand the future in which the current aircraft park continues to operate without the use of new aviation technologies that could reduce fuel consumption and reduce emissions.

Scenario 1 assumes a 5% detour factor for the route network for flights around the world. This factor considers the influence of weather, inefficiency of the route and manoeuvering around the terminal.

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

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

Annual global fuel consumption results were calculated for each scenario described. Table 4.10 provides us with a summa of the annual fuel consumption estimates for all four scenarios studied.

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

Table 4.10: The results of modelling the annual global fuel consumption (in billions of kilograms for all scenarios)

Figure 4.56 shows us the same information in graphical form. It is clear that scenario 3 means the use of high-speed introduction of NASA N + 2 aircraft has the most positive impact on the environment. Fig. 4.57 shows us the annual fuel consumption by commercial aviation for seven regions of the world in the assumptions made for scenario 3. Tendencies indicate that Asia is a region that is expected to have more flights and, therefore, more fuel used in 2040. In Scenario 3, it is expected that the annual fuel consumption used in Asia will increase by 86% from 63 billion kilograms to 117.5 billion kilograms.

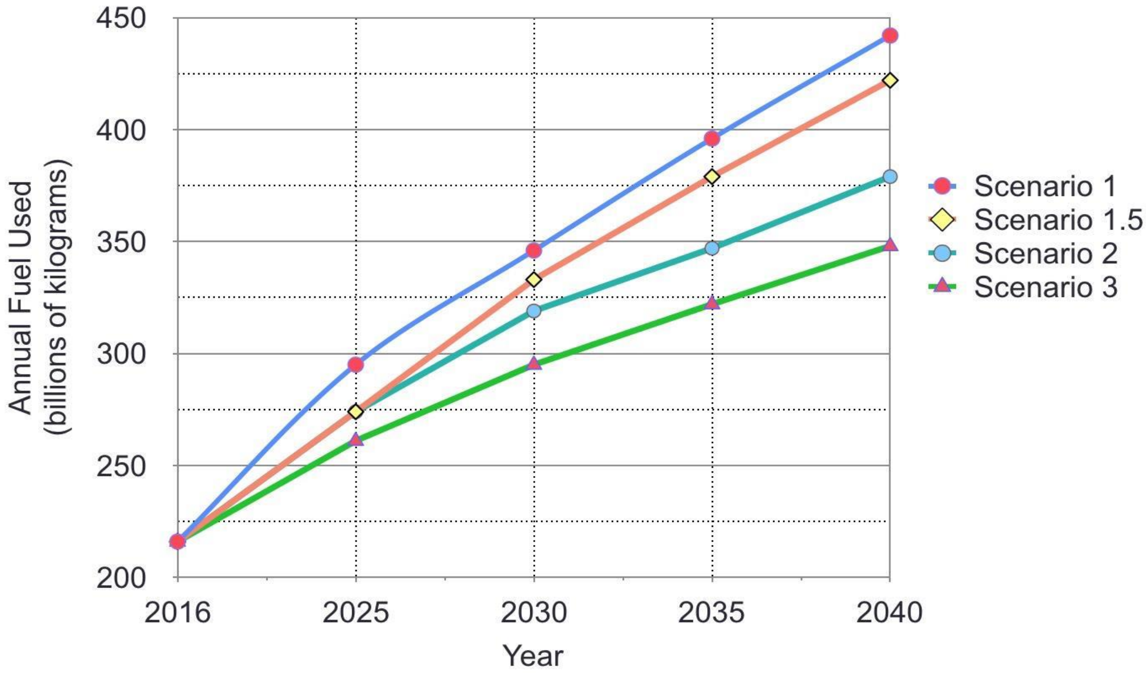


Figure 4.56: Annual global fuel consumption for all simulated scenarios

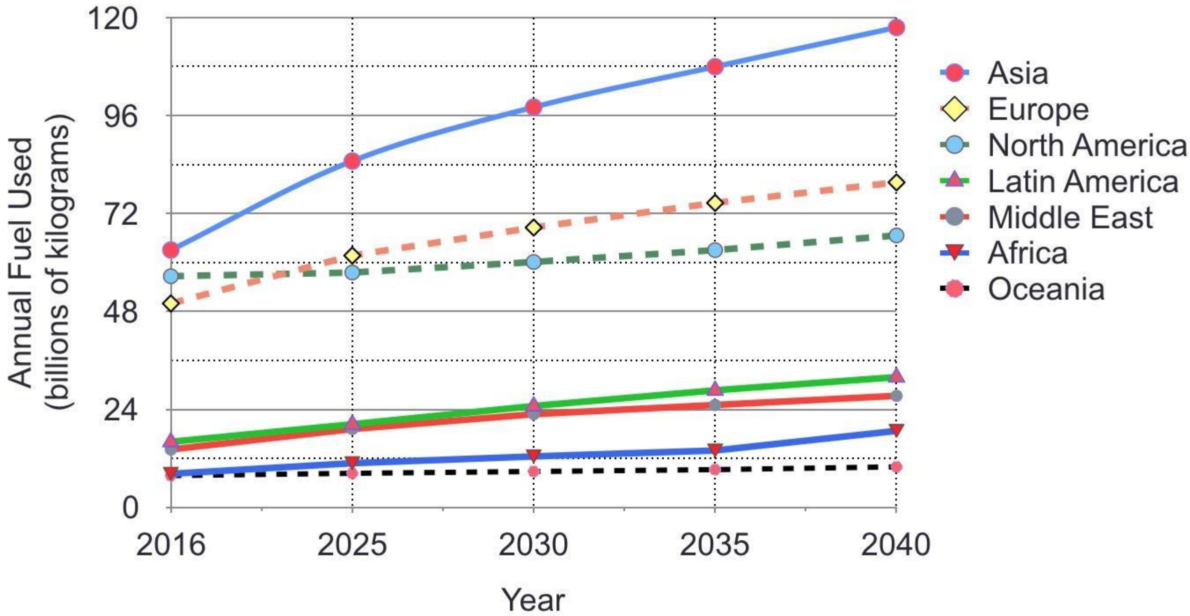


Figure 4.57: Annual projected fuel consumption by region

Figure 4.58 shows us the annual fuel consumption for distinct countries. The graph compares the annual fuel consumption between the US and the BRIC countries. China appears to be the country with the largest change in annual fuel consumption for commercial aviation between 2016 and 2040. Even with the introduction of NASA's N + 2 generation of aircraft in 2030, it is expected that in 2040 China will consume 113% more aviation fuel than in 2016 due to the significant growth in aviation operations in the country.

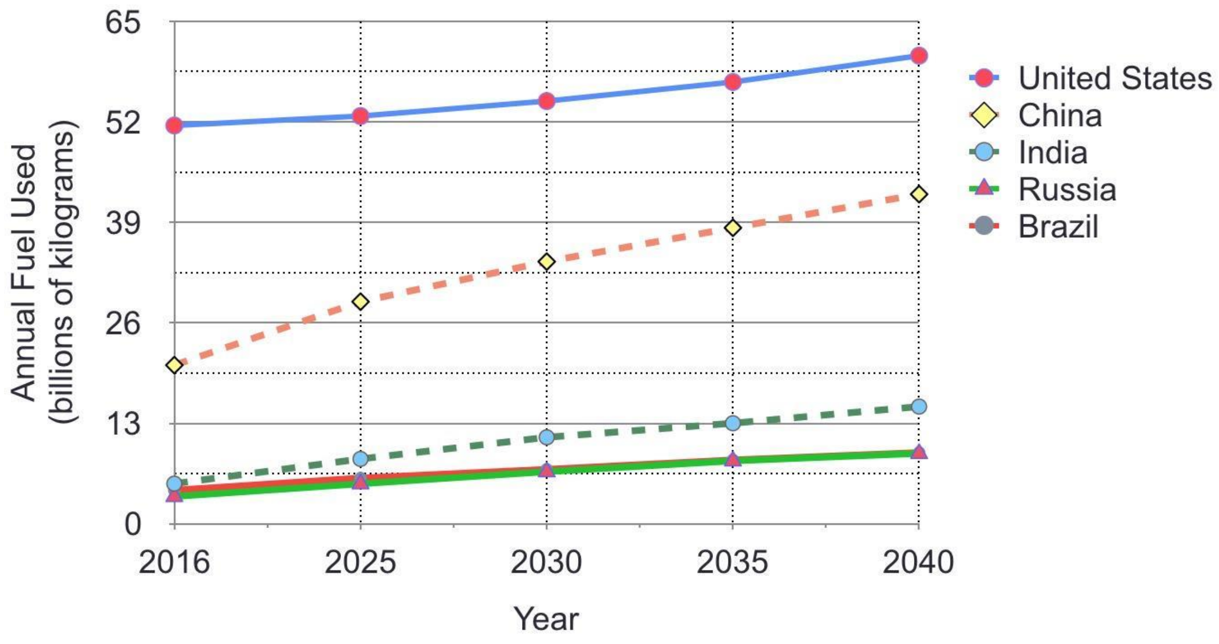


Figure 4.58: Annual fuel consumption for selected countries

Figure 4.59 shows the annual fuel consumption in 2040, which corresponds to each 1x1 degree cell on Earth for scenario 3. The map shows the regions of the world (including airspace corridors) with heavy fuel use. For example, countries being highlighted are China, the European Union, South-East Asia, the Middle East, as four regions where a high concentration of fuel consumption is expected in 2040. The projected reduction in emissions of pollutants for the LTO cycle in 2030, 2035 and 2040 for scenario 3 related to the emission level corresponding to scenario 1.5 is shown in Figure 4.60

Fig. 4.61 shows global annual CO_2 emissions for all four scenarios observed during the analysis. The introduction of NASA's N + 2 generation aircraft in large numbers (scenario 3) has reduced global CO_2 emissions from aviation activities in 2040 by 17.6% compared to scenario 1.5, i.e. introduce the only aircraft of the generation N + 1. In case of bringing into service a large number of N + 2 generation aircraft up to 2040, it is possible to reduce CO_2 emissions by 234 billion kilograms per year

Fig. 4.62 shows the results of CO_2 emissions for the regions of the world for scenario 3. Fig. 2.13 shows the annual CO_2 emissions for distinct countries. The graph compares the annual CO_2 emissions produced by the US and the BRIC countries. China is the country with the largest change in annual fuel consumption for commercial aviation between 2016 and 2040. Even with the introduction of NASA N + 2 aircraft in 2030, it is expected that China will produce emissions in 2040 of CO_2 by 113% more than today.

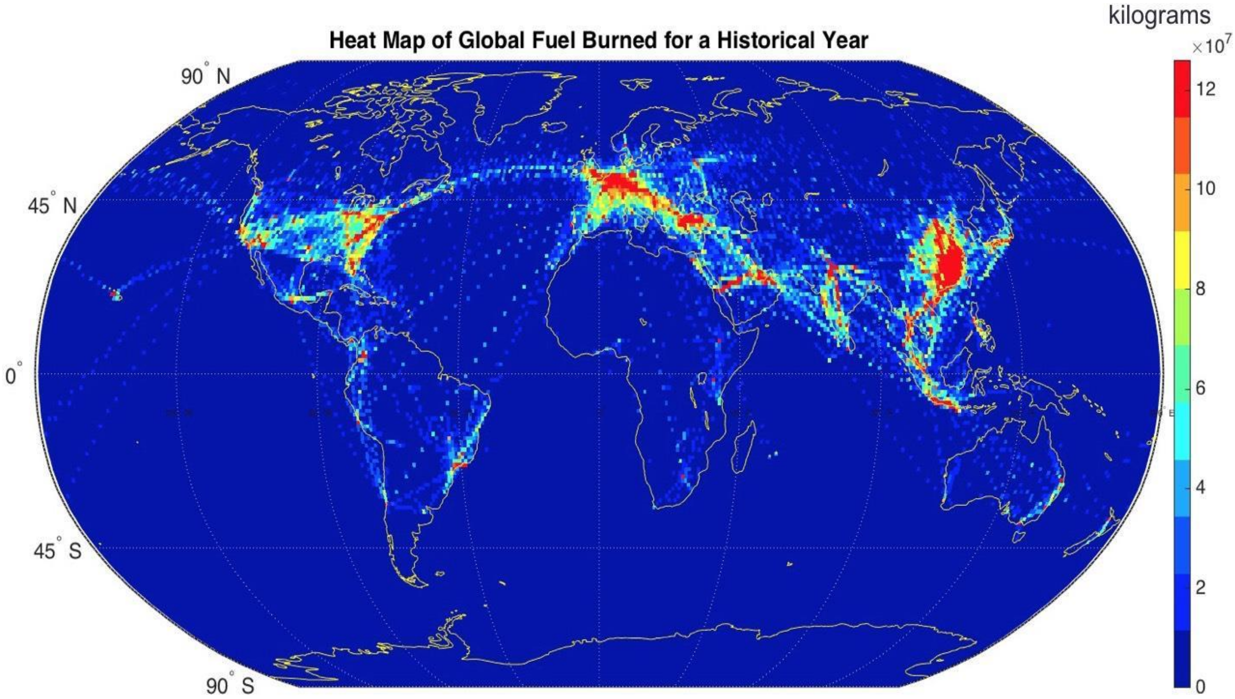


Figure 4.59: Annual fuel consumption for Scenario 3

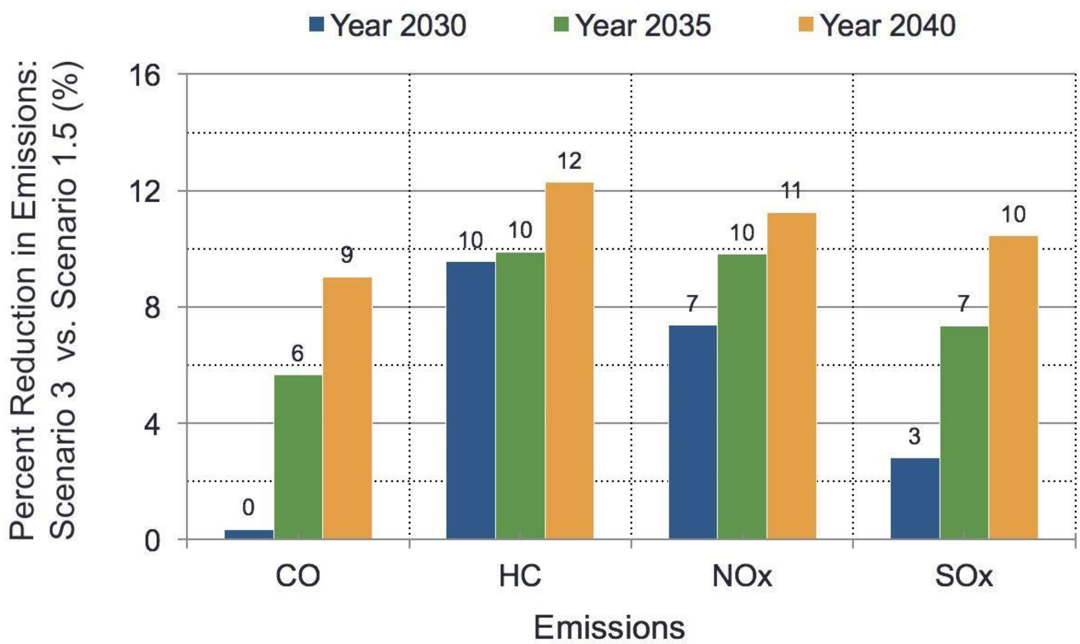


Figure 4.60: Annual emission reductions in the LTO cycle between scenarios 1.5 and 3

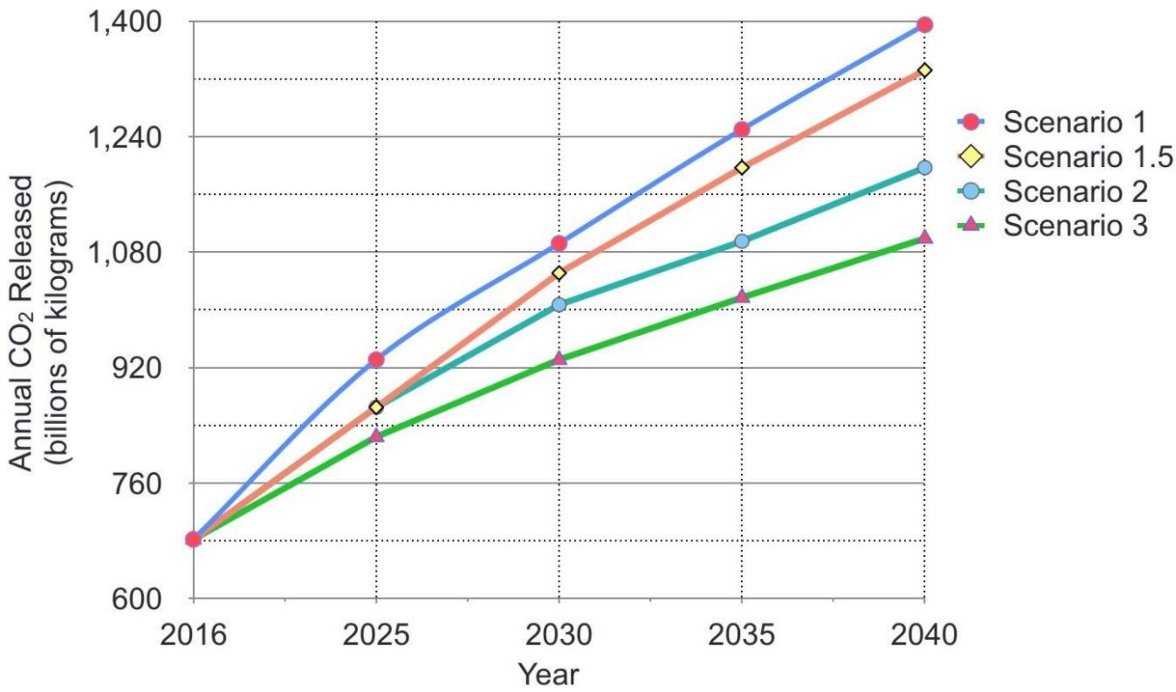


Figure 4.61: Annual CO_2 emissions produced by commercial aviation for all scenarios

Figure 4.64 shows the annual CO_2 emissions in 2040 corresponding to each 1x1 degree cell on Earth for scenario 3. The map shows the world regions (including airspace corridors) with high intensity of CO_2 emissions. For example, the most highlighted countries on the map are China, the countries of the European Union, South-East Asia and the Middle East as regions where a high concentration of CO_2 emissions expected in 2040.

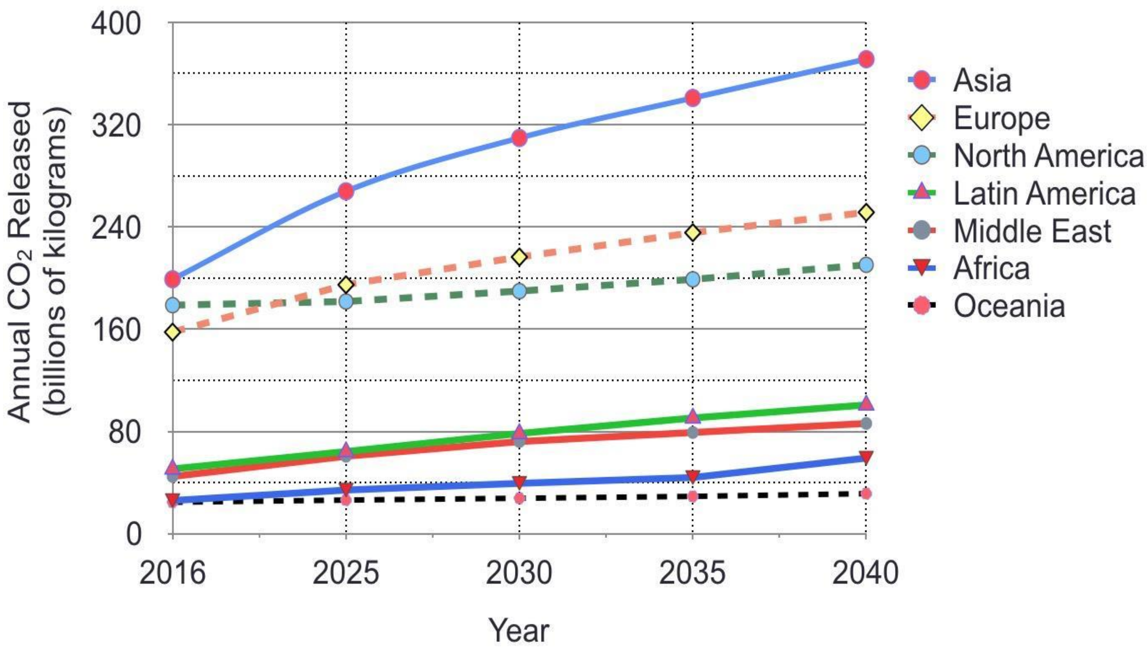


Figure 4.62: Annual CO_2 emissions produced by the regions of the world according to Scenario 3

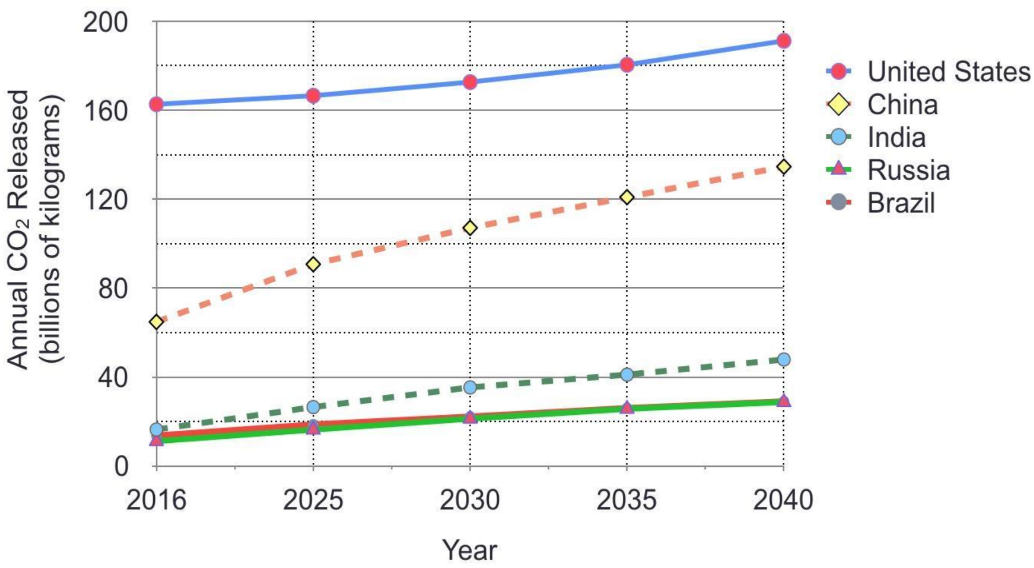


Figure 4.63: Annual CO_2 emissions for selected countries under Scenario 3

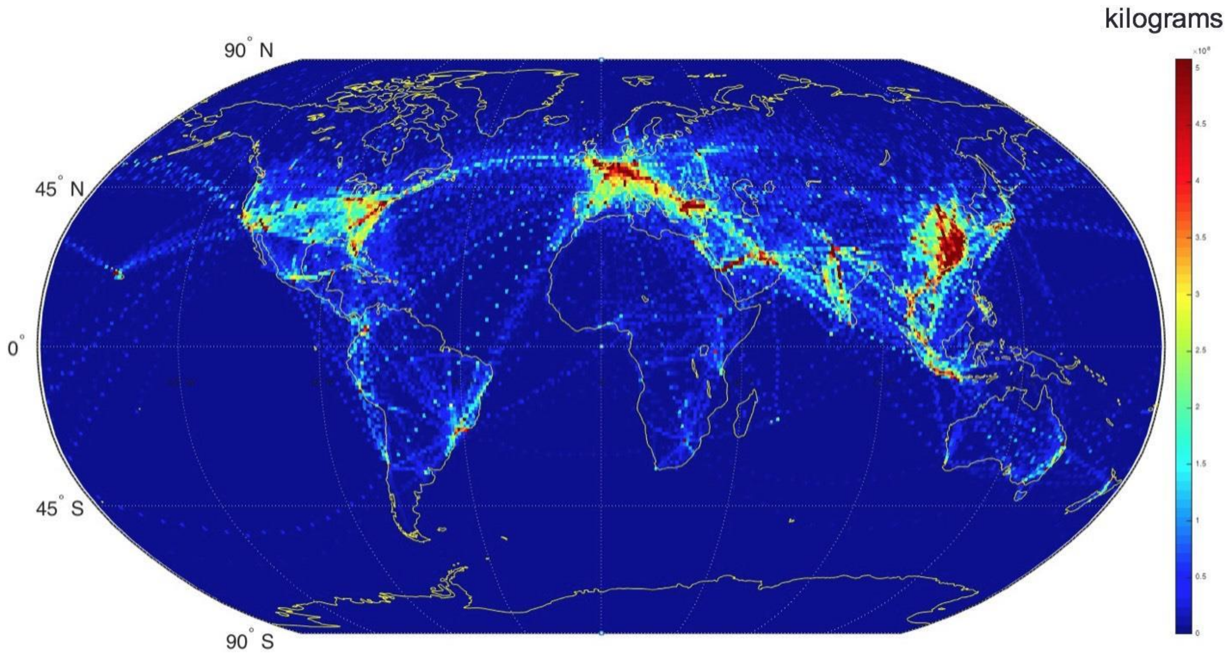


Figure 4.64: Annual CO_2 emissions calculated for each 1 × 1 cell for Scenario 3

Another significant impact on CO_2 emissions worldwide are:

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

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

In Figure 4.65 the results of the GDM fuel usage model are compared with the target level of the ICAO specific fuel consumption reduction. The ICAO model assumes a 2% reduction in fuel consumption each year. It is shown that ICAO's technical goal for a 2% reduction in fuel consumption per year yields results similar to those in Scenario 2, so the introduction of NASA N + 2 generation in modest quantities since 2030. Scenario 3 provides a higher fuel economy compared to the ICAO technical goal, as shown in Figure 4.65.

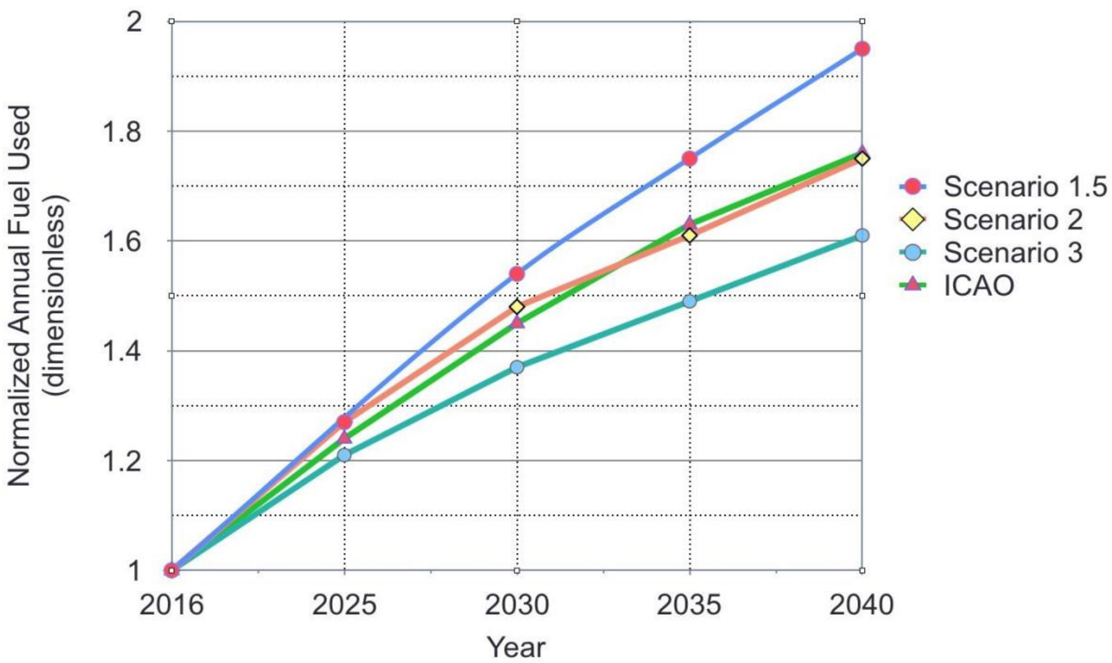


Figure 4.65: Comparison of normalized fuel consumption tendencies for scenarios 1.5, 2, 3 and the goal of ICAO: 2% global annual increase in fuel efficiency

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

In the work [Ploetner, K. O., et al., 2017] quantitative assessment of the impact of the potential development of aviation technology, increasing of production and improving the infrastructure use on global CO_2 emissions from the fleet of aircraft until 2050 is provided. In the work for the basic scenario, the state of the aviation industry in 2017 is accepted, i.e. the assumption that in the period 2017-2050 reduction technologies for the specific fuel consumption will not be introduced. The numerical model of the global aircraft fleet is used for a quantitative evaluation of the total fuel consumption and reduction of carbon dioxide emissions. There is a prediction of a total reduction in aviation fuel consumption by introducing new aviation technologies by 2050 and it is in the range between 17% and 27% relative to the baseline scenario. The increase in aircraft performance due to the increase in the load factor, passenger capacity and more intensive use of aircrafts further reduces the level of fuel consumption by the aircraft fleet by 7-8% by 2050 relative to the baseline scenario.

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

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

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

Fig. 4.66 shows the types of next generation aircraft and the predicted level of fuel efficiency improvement [Randt N. P., Jessberger C., Ploetner K.O., 2015]. However, despite these significant efforts to develop new or modernized aviation programs aiming to improve fuel efficiency, it is clear that the goal of achieving a CO-neutral growth after 2020 will not be achieved. Currently, according to Boeing, more than 14,870 single-aisle planes are in operation and more than 28,140 aircraft are expected to come over the next 20 years, and according to Airbus, an even larger number of 20,600 aircraft are in operation (for 2017) and is expected to increase to 34,900 aircraft (for 2036). [Airbus_Global_Market_Forecast_2017-2036]. Even at the current production rate of about 120 aircraft per month, for the Airbus A320 and Boeing 737 families of aircrafts, the very high level of new and more efficient aircraft entering the market slows the achievement of common ambitious targets for emission reductions at the level of the world aircraft fleet [Ploetner K.O., et al., 2017].

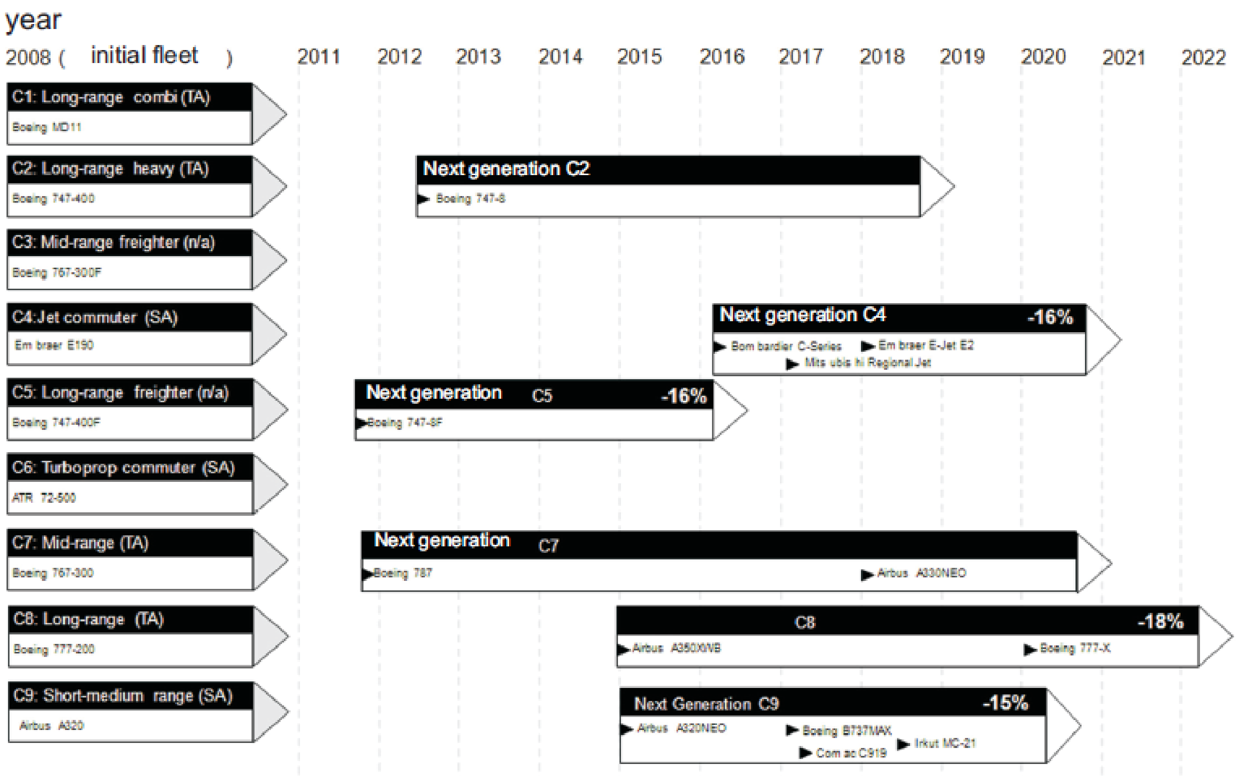


Figure 4.66: Next-generation aircraft types and associated "benefits" in fuel efficiency

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

For aviation technologies and configurations, three scenarios for fuel consumption reduction accounting at the aircraft level were considered.

Scenario 1.1 assumes that the aviation industry can develop and supply new aircraft with reduced fuel consumption (up to 43%) between 2020 and 2035, and 60% reduction in fuel consumption between 2035 and 2050 years.

In Scenario 1.2, between 2020 and 2035, fuel consumption is expected to be reduced by 22% for the aircraft, given that most of the current programs will be upgraded [Schilling T., Rötger., T, Wicke, K. 2016], and between 2035 and 2050 it is assumed that the aviation industry can provide a 60% reduction in fuel consumption volume for all aviation programs (48% reduction for scenario 1.3).

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

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

The conservative scenario includes incompletion of the SRIA 2035 and 2050 targets for reducing fuel consumption, increasing production, and increasing aircraft performance during the next six years.

The ambitious scenario includes incompletion of the SRIA 2035 goals of reducing fuel consumption, expanding production and increasing aircraft performance for three years, and also takes into account modifications and upgrades for the current fleet of aircraft.

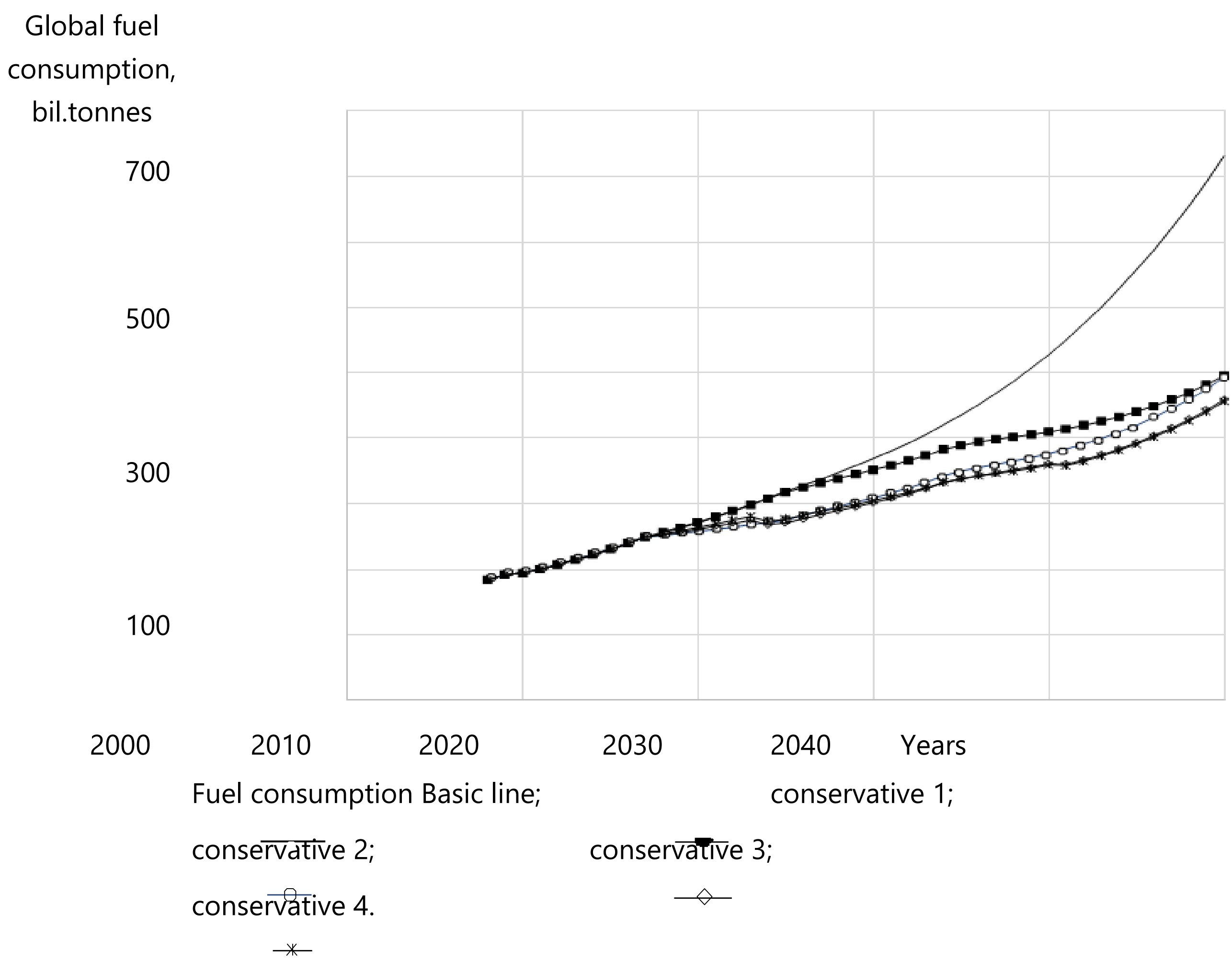
The radical scenario includes the introduction of new aircraft programs meeting the objectives of the SRIA until 2050, increasing production and increasing the production rate of aircraft (up to one year), reducing the growth rates of regional RPKs to 50%. At the regional level, a stronger transition from air transport to land, as well as modifications and upgrades for the current fleet of aircraft is expected.

In addition to the consolidated three scenarios, each case was consistently calculated within each scenario, and a summary of the simulation results for all the sub-variants in each of the scenarios is given in the work [Ploetner, K.O., et al., 2017].

Authors also analyzed the impact of aviation technologies and production capabilities, possible options for emission reductions at the operational level were, for example, by changing aircraft performance. In case 3.1, the average load factor increases to 95% (from 80.4% in 2015) [IATA, Fact Sheet Industry Statistics, 2017]. In the case of 3.2, the average number of installed sites is increased by 10% for all aircraft programs considering additional fuel consumption. In case 3.3, the average aircraft load (measured by the number of flights per year) is increased by 10%.

In case 4, regional RPK growth rates within the EU, North America and Asia have halved between 2017 and 2050, using the initial growth rate provided by Boeing [*Boeing, Boeing Current Market Outlook 2015-2034*] until 2035 with the assumption of unchanged growth rates until 2050. In case 5, decisions were made to reduce fuel emissions with a 4% reduction in fuel consumption for an operating fleet of aircraft.

As shown in Fig. 6.67 The introduction of new aviation programs with lower fuel consumption (22% in 2020-2035 and 48% in the period 2035-2050) leads to a significant reduction in fuel consumption in the entire fleet of aircraft for the "Conservative 1" scenario in comparison with the base level after 2035. Increasing the productivity of airplanes by increasing the load factors (conservative 2-4) and the average number of installed sites (conservative 3-4) can further decrease of growth in fuel consumption of the fleet of aircraft after 2020. As the results of modelling show, due to the complex improvement of aircraft, it is possible to reduce fuel consumption of the aircraft fleet in 2024-2025, but after 2025 the simulated aircraft productivity increases will reach their limiting value, therefore the forecasted fuel consumption again begins to increase. This model, based on static aircraft statistics, does not take into account the effect of the reduction in aircraft lifetime due to the increase in the load factor (conservative 4) and therefore does not simulate a reduction in fuel consumption during the renewal of the fleet of aircraft.


Global fuel
consumption,
bil.tonnes
700
500
300
100
2000
2010
2020
2030
2040
Years
Fuel consumption Basic line;
conservative 1;
conservative 2;
conservative 3;
conservative 4.

:

Figure 4.67: Forecast of fuel consumption by the aircraft fleet from 2008 to 2050 for basic and conservative scenarios 1-4

A similar effect of increasing aircraft productivity can be observed for ambitious and radical scenarios. In the "Conservative 1" and "Conservative 2" scenarios, similar fuel consumption values were achieved for the fleet due to the same load factors in 2050.

Comparing conservative scenarios 1-4 with the baseline, it can be seen that fuel consumption by the fleet of aircraft can be reduced by 40% (conservative 1) and up to 45% (conservative 4) in 2050. Comparing the results of fuel consumption to 2050 with fuel consumption in 2008, it can be seen that the fuel consumption of the fleet of aircraft will increase 4.5 times for the base level, 2.7 times for "Conservative 1" and 2.5 for "Conservative 4 ".

Comparing the scenarios with the lowest level of fuel consumption, such as "conservative 4", "ambitious 5" and "radical 6" with a baseline level, and also with the ATAG goals, as shown in Figure. 4.68, it can be seen that even for the "radical 6" scenario, it is impossible to achieve negative fuel [illegible]on on an annual basis.

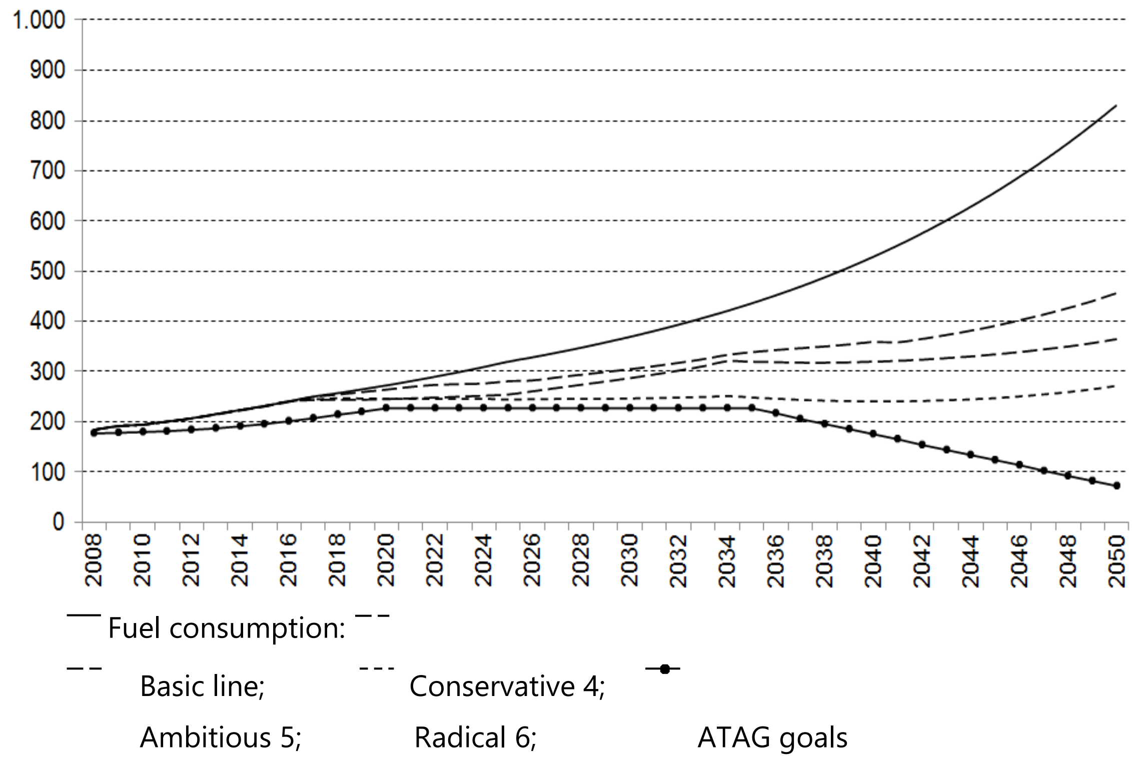


Figure 4.68: Forecast of fuel consumption for the aircraft fleet for the scenarios under study and the target ATAG level period 2008 to 2050

It can be seen from Figure 2.18 that the requirement to provide a CO-neutral increase can almost be met until 2050 in the case of the "radical 6" scenario. Nevertheless, works to ensure the introduction of promising modifications, with an average reduction in fuel consumption by -43% to 2035 and -60% in the period from 2035 to 2050, for the whole fleet of passenger aircraft from regional turboprops to large long-range aircraft require large costs by the aviation industry. It is estimated in the work [Ploetner, K.O., et al., 2017] that the considered level of improvement in aviation technologies, as well as the slowdown in RPK growth, will not fully meet the ATAG 2050 goal: to cut the total by 2050 the amount of CO_2 emissions compared to the 2005 level. The authors note that to achieve the target level of CO_2 emission reduction, the widespread use of alternative fuels is required.

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

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 per cent annual fuel efficiency aspirational goal. Sustainable alternative fuels have the potential to make a significant contribution, but sufficient data are not available to confidently predict their availability over the long term. Also, considering only aircraft technology and operational improvements, additional measures will be needed to achieve carbon-neutral growth relative to 2020.

Figure 4.69 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.

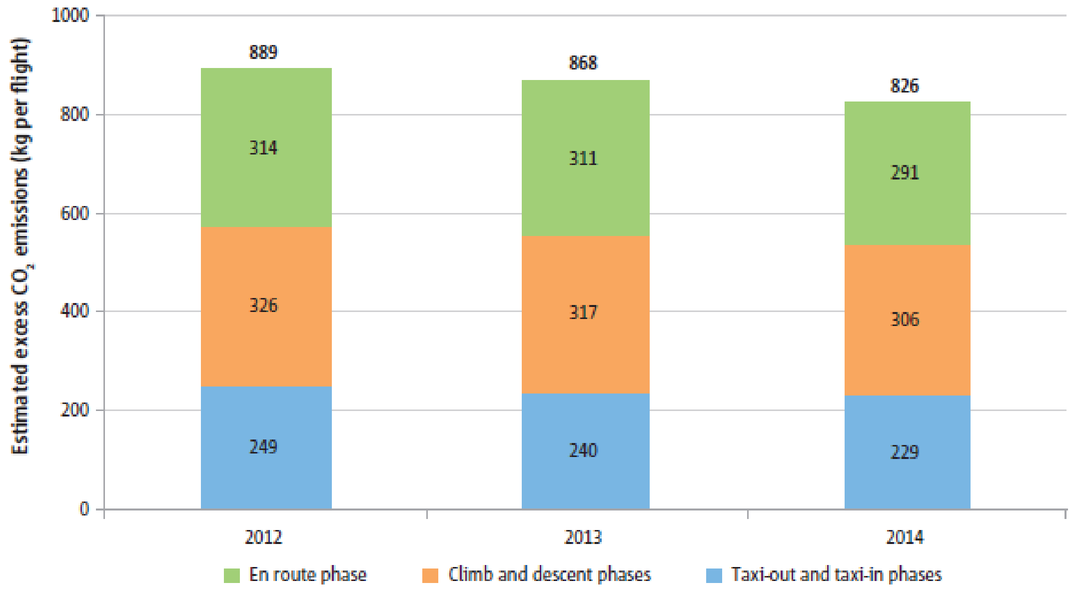


Figure 4.69: Estimated excess CO_2 emissions per flight are decreasing in taxi, take-off, climb/descent and en route phases

FORUM-AE's reference when assessing European progress towards ACARE emissions CO2 & NOx goals is shown in the Figure 4.70. One should also note that NOx emissions are considered either at local level when addressing air quality concern or at global scale when addressing climate change. Still referring to SRIA Vol. 1, Appendix, the timing assumption to progress towards CO2 & NOx goals is the following [FORUM-AE]:

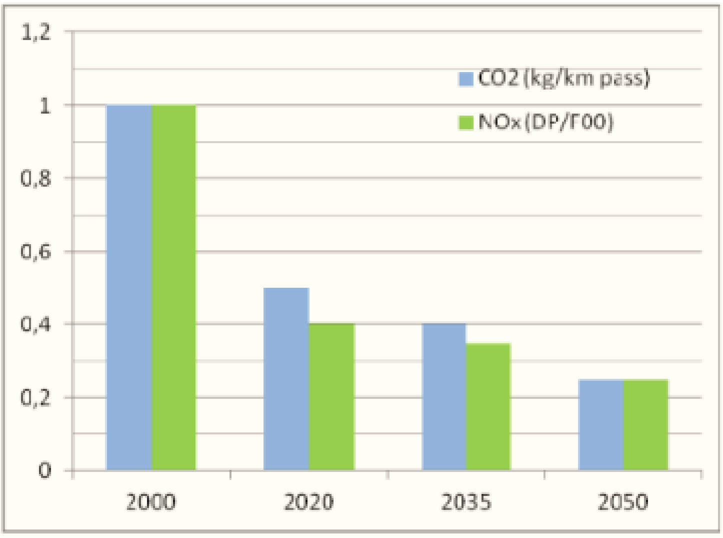


Figure 4.70: ACARE CO2 & NOx goals calendar (using CAEP6 margin for NOx) [FORUM-AE]

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

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

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

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

The 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.

A 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 to ensure both NOx & nvPM ambitious low levels: enhanced lean combustion in general (achieving TRL6 maturity & extending its application to a smaller size and/or smaller OPR engine combustors), and focus on more specific aspects which may be beneficial to particles reduction (improved atomisation);
- The modelling of emissions, which for particles emissions is far from being predictable today, because of the physical complexity of particles formation (gaseous precursors formation, particles nucleation & oxidation…), and the modelling of combustion-related operability aspects;
- The experimental analysis, which is 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 CO_2 emissions and 3% of the total EU CO_2 emissions. It was also estimated that European aviation represented 22% of global aviation's CO_2 emissions. Similarly, aviation now comprises 14% of all EU transport NOx emissions and 7% of the total EU NO_x emissions. In absolute terms, NO_x emissions from aviation have doubled since 1990, and their relative share has quadrupled, as other economic sectors have achieved significant reductions [EEA, Transport and Environment Reporting Mechanism 2014].

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 show some signs of growing economic and connectivity benefits from aviation (measured in passenger-kilometres flown) without a proportionate increase in environmental impact (Figure 4.71). The diverging trends of passenger-kilometres flown and noise energy between 2005 and 2014 have shown that this is possible and that there is the potential for this to continue in the future. Nevertheless, the absolute noise energy and emissions of aviation are expected to grow further in the next twenty years.

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

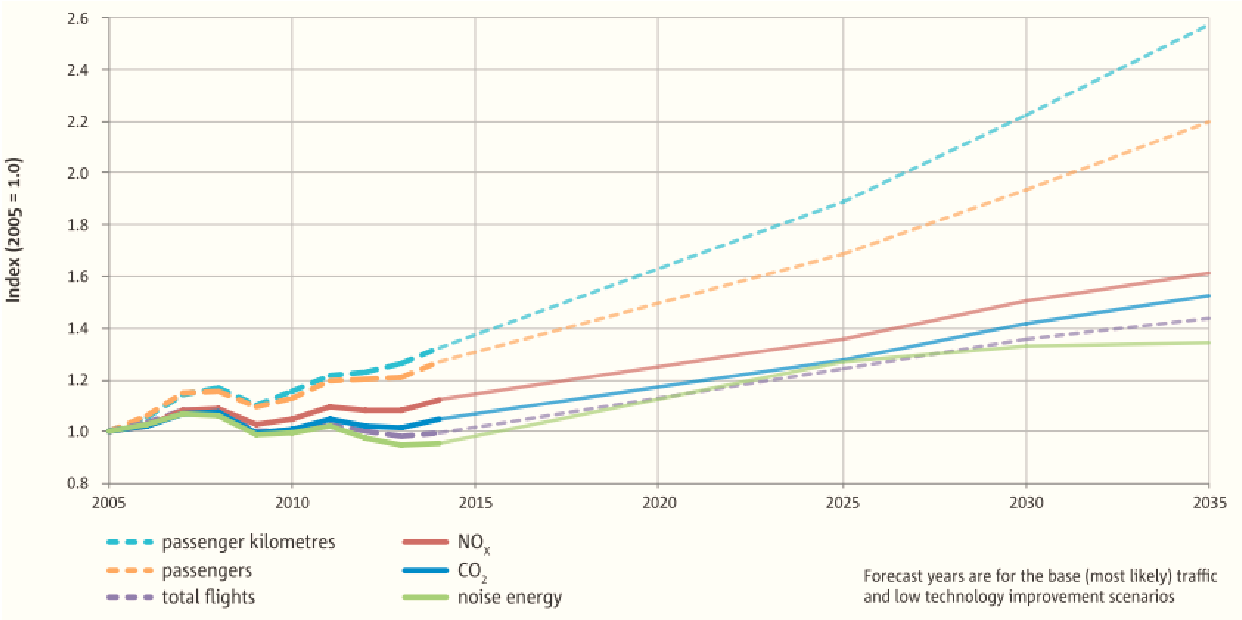


Figure 4.71: Noise and emissions forecast to grow slower than passenger kilometres

The connections between aviation emissions and radiative forcing, climate change, and its impacts and potential damages are shown in Figure 4.72. The principal greenhouse gases (GHGs) emitted are carbon dioxide (CO_2) and water vapour (H_2O). Emissions of nitrogen oxides (NOx) impact the concentrations of other GHGs, mainly ozone (O_3) and methane (CH_4). Black carbon (soot) is a directly emitted aerosol, and sulphur oxides (SO_x), NO_x, and hydrocarbons (HC) lead to aerosol production after emission. Water vapour emissions in combination with emitted or background aerosol lead to contrail formation. Persistent contrails, which form at high ambient humidity and low temperatures, increasing cloudiness. Additionally, aviation aerosol may modify natural clouds or trigger cloud formation. There is high confidence that these are the primary pathways by which aviation operations affect climate.

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.

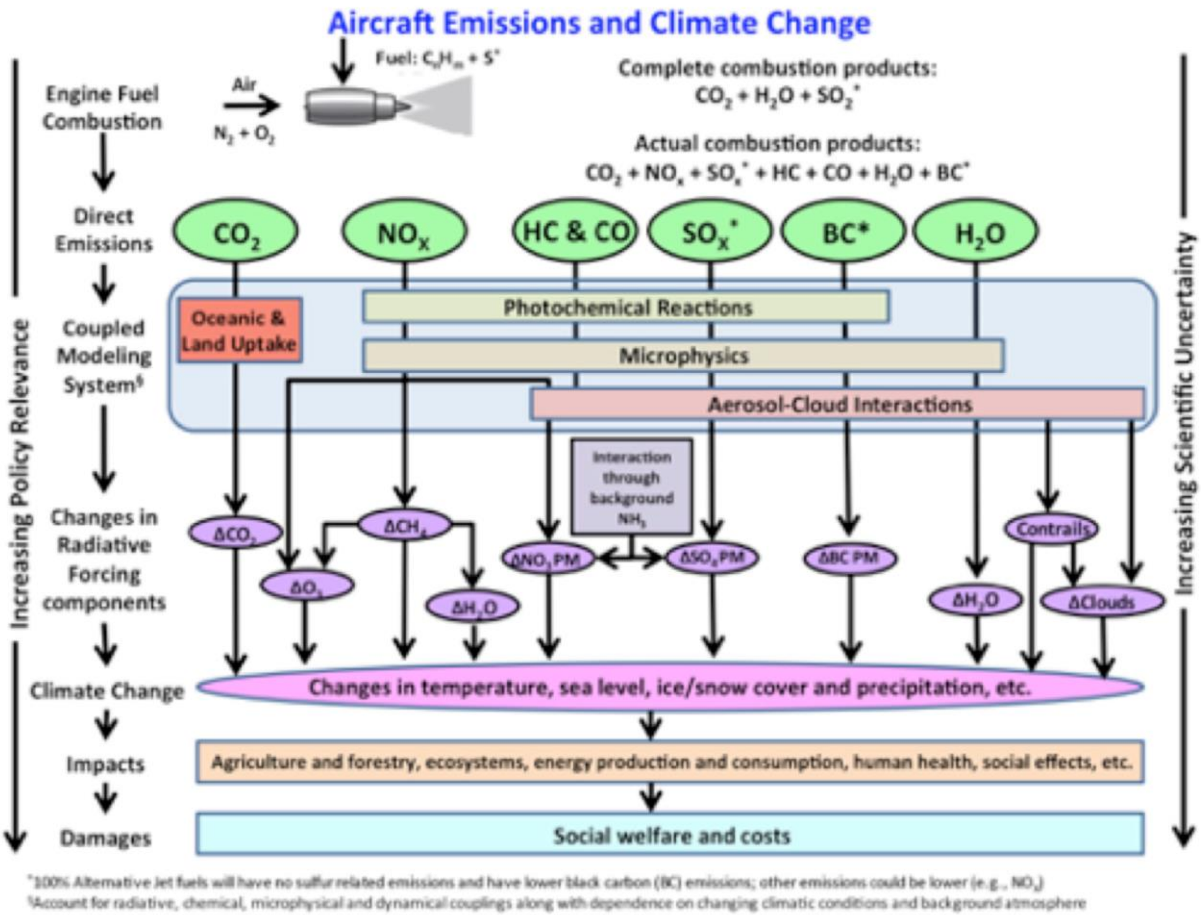


Figure 4.72: Updated schematic of the principal emissions from aviation operations and the relationship of emissions to climate change and impacts. The terminology, ΔX, indicates a change in component X. The term ΔClouds represents contrail induced cloudiness and aerosol-cloud interactions. (From Brasseur 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 newly published results available, for example, for contrails, contrail cirrus and indirect cloud effects. An updated science assessment would also identify important remaining gaps in understanding and, hence, guide future research directions.

Aircraft CO_2 emissions increased from 88 to 156 million tonnes (+77%) between 1990 and 2005 according to the data reported by EU28 and the EFTA Members States to the United Nations Framework Convention on Climate Change (UNFCCC) (Figure 4.73). 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.

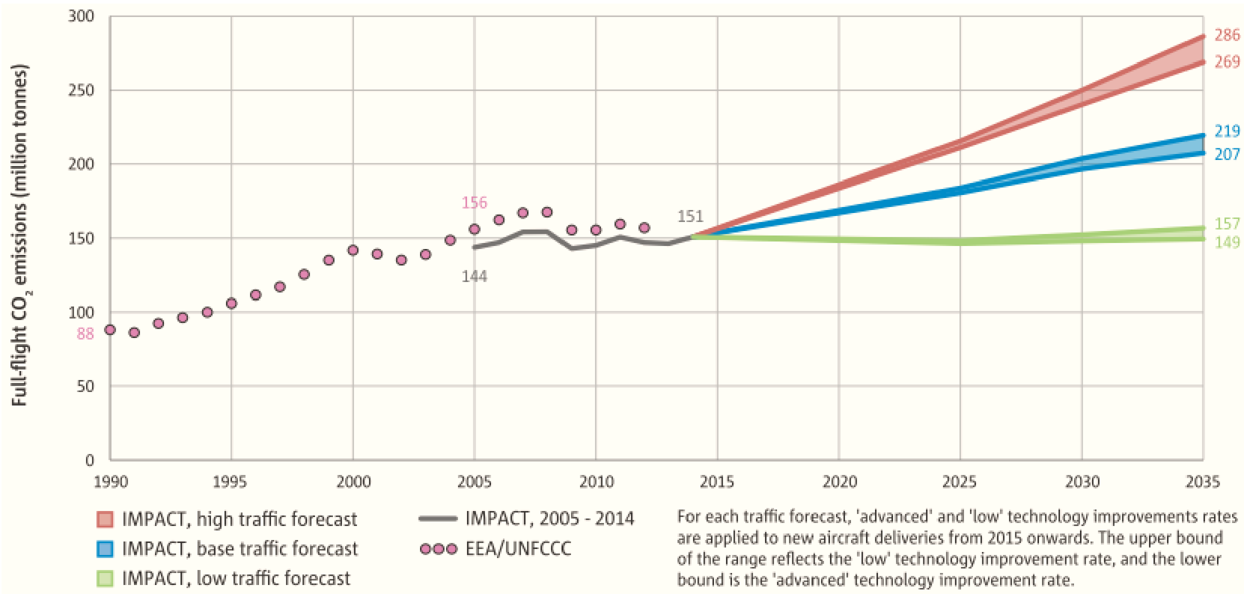


Figure 4.73: After remaining stable between 2005 and 2014, aircraft CO_2 emissions are likely to increase further

NO_X emissions have also increased significantly (Figure 4.74): +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).

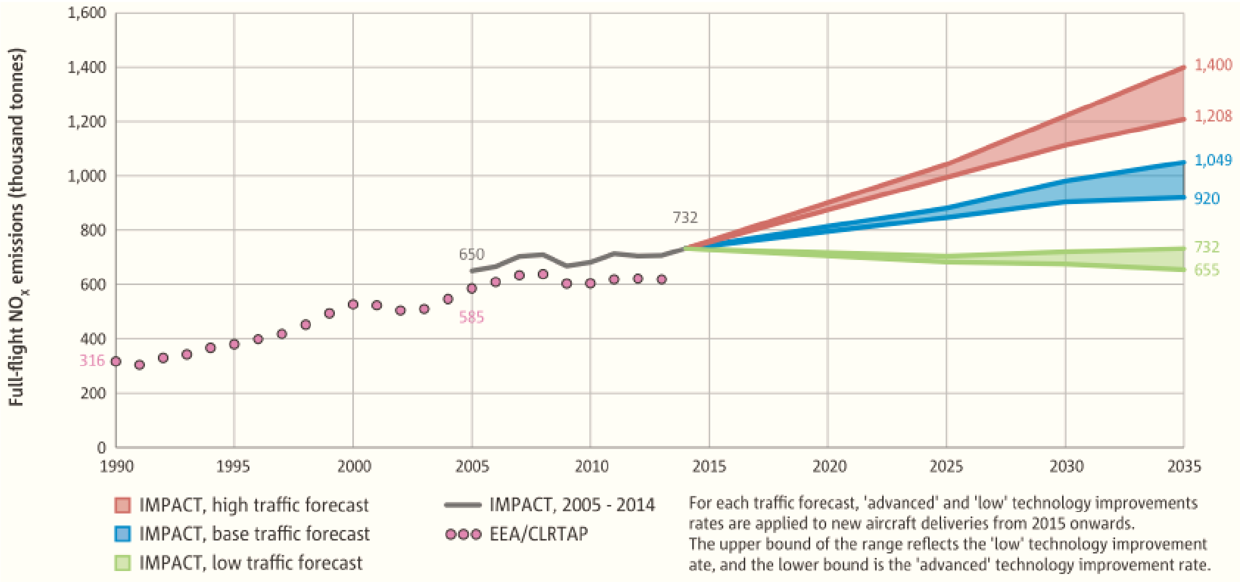


Figure 4.74: NOx emissions are likely to increase in the future, but advanced engine combustor technology could help mitigate their growth

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 4.75). 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.

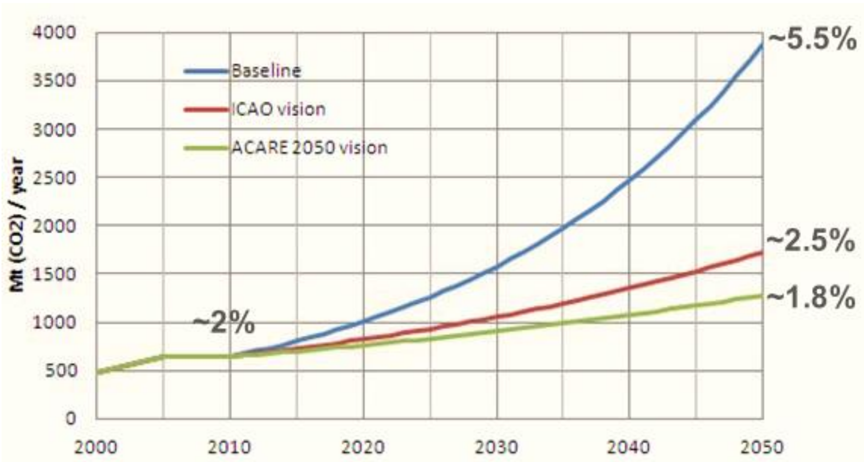


Figure 4.75: Global aviation CO_2 forecast with ACARE assumption

(Assumptions: ACARE 2050 is achieved in 2050 and fully introduced in the 2050 fleet; there is a conti nuous improvement 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 CO_2 and NO_x goals and is summarized in the following Table 4.10. 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).

When the electric-powered aviation will be created, the next step will be the integration of cardanic engine system that will improve drastically the manoeuvring ability. Consequently, the requirement will disappear for ailerons, vertical rudders and horizontal stabilizers, without which does not go any aircraft in the world.

To illustrate, in Figures 4.76-4.80 are shown new aircraft projects and their power plants of different air companies in the world [*http://theconversation.com/what-commercial-aircraft-will-look-like-in-2050-33850*].

	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 4.10: FORUM-AE assessment against ACARE emissions goals [FORUM-AE]

Figure 4.76: Project of E-Thrust (EADS)

Figure 4.77: Project of Boeing & NASA

Figure 4.78: Project of Airbus 2050 - Bionic Aircraft

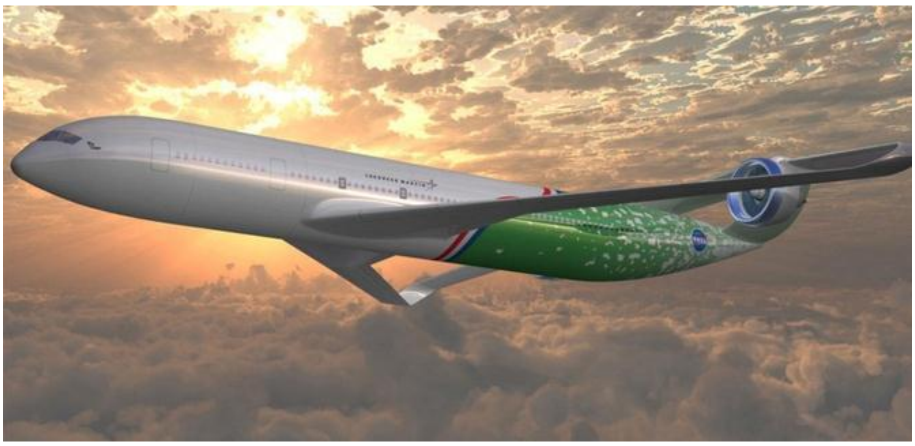


Figure 4.79: NASA's project of electric aviation

Besides the known aircraft projects, the European aerospace consortium Airbus Helicopters has developed a light helicopter Bluecopter, which, due to the technologies involved in its development, is significantly more cost-effective and environmentally compliant machine of this sort (Figure 4.81). The created helicopter is a demonstrator of the used technologies [*http://www.helicopters.airbus.com/ website/en/press/Eco-friendly-and-eco-efficient-technologies-of-tomorrow-take-to-the-sky-with-Airbus-Helicopters%E2%80%99-Bluecopter-demonstrator_1801.html*].

Figure 4.80: Project of Prandtl Plane Airfreighter (Pisa University)

Figure 4.81: Bluecopter helicopter

The helicopter features an improved five-bladed lifting propeller, in which the noise reduction technologies are used. The shape of the lifting propeller ensures noise-level reduction at least by three-four decibel. The Bluecopter engines are controlled by special software support. For ensuring greater efficient performance, during the flight one of two engines is deactivated, while the power rate of the other one is increased. The technologies used in the Bluecopter permit to reduce fuel consumption by 40 % relative to the conventional light helicopters, to reduce the carbon oxide emissions and reach noise level reduction by 10 decibels.

The company Airbus Helicopters announced about two-year conception development phase for new model of heavy helicopter. The future flagship under the code name X6 will be a modern alternative for the H225 and will permit the manufacture continuing further to maintain the positions in the transport sector (Figure 4.82).

According to Airbus Helicopters, the X6 shall continue the success of H160 during the next decade H160, but within the heavy-machine class, and its conception also shall become determinative one in the helicopter industry for decades ahead *[http://www.helicopters.airbus.com/website/en/press/_1771.html]*. The X6 project will establish new standards in the industry not only in designing but also in manufacturing strategy because this project is based on all newest technologies and production capacity.

The German design institute Bauhaus Luftfahrt that belongs within the Airbus concern, announced about its intention to carry out, at the year of 2022, tests of a "more electric aircraft" with hybrid thrust [*https://nplus1.ru/news/2016/02/08/hybrid*]. The plans call for carrying out tests of a decreased unmanned aircraft model, and the checks itself will be carried out within the frames of the European program Clean Sky 2, focused on creating environmentally compliant and cost-efficient civil aviation.

Figure 4.82: Project of advanced heavy helicopter X6

The development is carried out within the framework of the DISPURSAL project, according to the propulsive fuselage technology. In the advanced "more electric aircraft" will be used two diminished turbofan engines that will not only be responsible for the aircraft movement but also will generate electric power for energizing its onboard systems and the fan electromotor mounted in its aft body. The contribution of this engine in shaping the total thrust makes up 23 %.

In the comparative simulation involved was an aircraft designed under the DISPURSAL project, of 340 passenger capacity and a flying range of 8…9 thousand kilometres. It was compared with a modern Airbus passenger aircraft A330-300. During the simulation, the airplanes were carrying out flights at a velocity of M = 0.78 (963 km/h). The efficient performance of the new airplane in comparison with the A330-300 will make up 38.3 %.

The "more electric aircraft" assumes using on the aircraft board ample quantity of electric systems. Generally, such a solution increases the total electric energy consumption, but it allows decrease the onboard equipment weight. For example, the total hydraulic system can be replaced by several local hydraulic systems with electric driven pumps providing required pressure.

Airbus has joined together the efforts with Rolls-Royce and Siemens for developing a flying demonstrator dubbed E-Fan X (Figure 4.83) that will broaden significantly the application of electric motors on the commercial aircraft. The E-Fan X airplane is a flying demonstrator on the scale of suburban distances (Figure 4.84).

The flying demonstrator E-Fan X on the scale of a suburban jet airplane comprises one electric motor that is energized by the turbo generator embedded into the fuselage. Realized, is a consequential, hybrid architecture of the aircraft. The power value of about 2 MW was selected because this is the upper limit available from the traditional technologies of electrical energy distribution, without the need of evolving the superconductivity or any other exotic approaches.

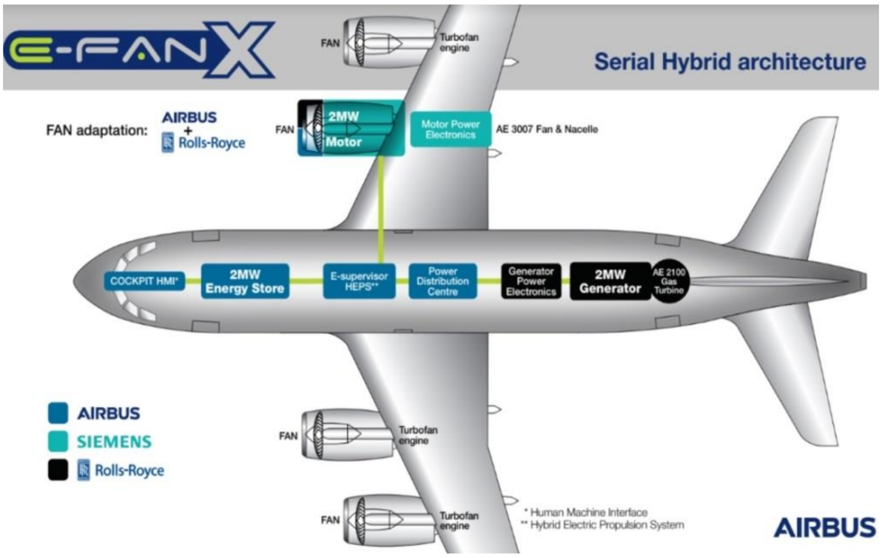


Figure 4.83: The plans of Airbus for creating an electric airplane

Figure 4.84: Project of E-Fan X

Integrative risks exist, such as thermal control, electro-magnetic interference effect, arcing, partial discharge and radiation exposure onto powerful electrical systems at altitude. The final objective is the creation of a hybrid-electric propulsion system for narrow-bodied aircraft at scales of A320 family and larger (Figure 4.85).

At present activities are extensively carried out on using distributed propulsion systems, with the energy from the turbine being transferred to the fan propellers either via mechanical transmission or in the form of electrical energy. In the latter case, the drive of the fan propellers is carried out using an electric motor. Expected reduction of specific fuel consumption at cruising rating (M = 0.8, H = 11 km) for this type of propulsion systems in comparison with the modern turbofan engines is estimated approximately in 15 % [*Единоепространствоинноваций (United area of innovations): http://mrgr.org/docs/detail.php?ID=507*].

Apart from the reduction of specific fuel consumption the possibility for suction of the boundary layer is being worked out, via the fans driven by the electric motors of the distributed propulsion systems (Figure 4.86).

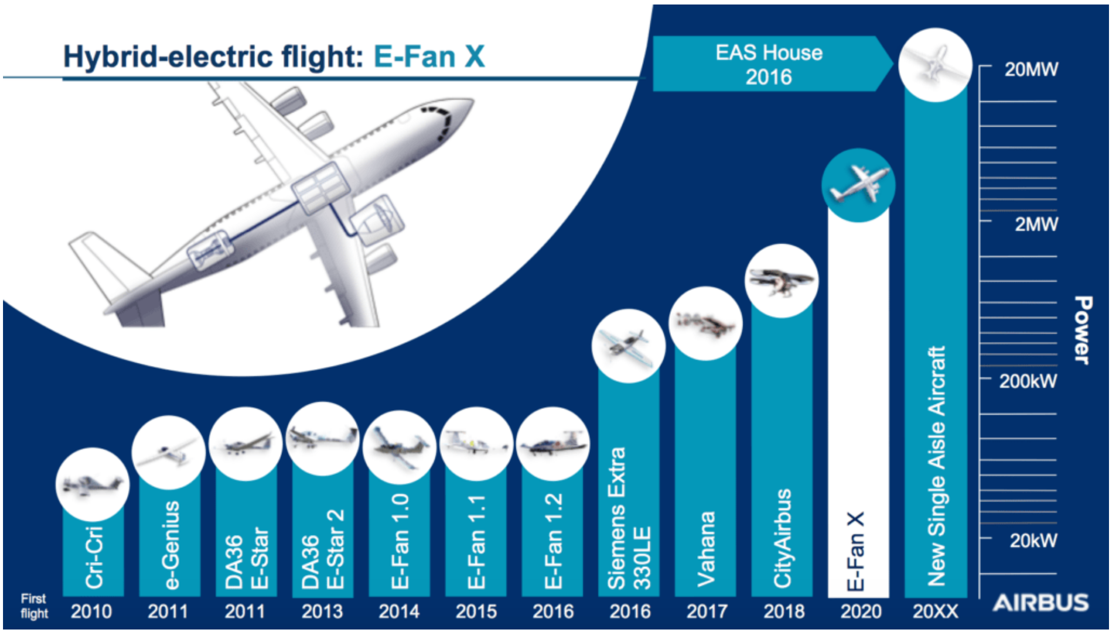


Figure 4.85– The plans of Airbus for creating an electric airplane

Some of the aircraft projects that are developed within the framework of long-range programs have other structural layouts (Figures 4.86-2.99). In the opinion of the developers, such configurations will permit the airplanes to overcome great distances using a minimal amount of fuel and comply with the environmental performance requirements. Together with the innovative technologies in propulsion engineering, this will permit the advanced airlines to be more cost-efficient in comparison with the modern airliners.

Figure 4.86: Projects of airplanes with distributed propulsion systems and boundary layer suction

Figure 4.87: Project of commercial airplane

Figure 4.88: Project of commercial airplane

Figure 4.89: Projects of commercial airplanes

Figure 4.90: Project of commercial airplane PARSIFAL

Figure 4.91: Project of light airplane

Figure 4.92: Project of flight airplane

Figure 4.93: Project of unmanned air vehicle

Figure 4.94: Project of commercial airplane

Figure 4.95: Project of supersonic airplane

Figure 4.96: Projects of commercial airplanes

Figure 4.97: Flying automobile DeLorean (passenger UAV (drone) Vahana)

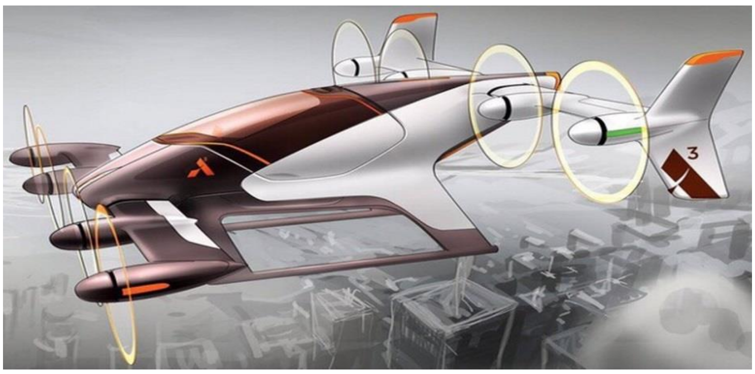


Figure 4.98: Project of light passenger airplane (air-taxi)

Figure 4.99: Project of passenger airplane

Thus, in short-term and mid-term prospects predominance of the turbofan bypass engines on heavy transport systems will be maintained. The improvement development of the propulsion systems will be directed, at first instance, on increasing the efficient performance both of the engine itself (at the expense of increasing the bypass ratio, elevation of gas temperature, compression ratio and so on) and of the aircraft in whole (use of conceptions "more electrical" aircraft, distributed propulsion systems, boundary layer suction, and so on).

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 to provide it to States and other stakeholders.

For example, the aircraft designed for (a) high cruise efficiency and low global emissions and (b) low noise and emissions at take-off and landing near airports may be quite different. The objective (b) leads to a glider like an aircraft with wide span wing and engine with a slow cold exhaust, for the low engine and aerodynamic noise and reduced emissions; this configuration has a low cruise speed and poor efficiency leading to longer travel times and higher fuel consumption and emissions in cruise flight. Conversely, the objective (a) leads to an aircraft with sweptback wings and high jet exhaust velocities for fast cruise and low fuel consumption and emissions that will be noisier and have more emissions near airports because of higher speeds and exhaust velocities at take-off and landing.

The multitude of engine and noise sources and the compatibility of low CO_2 and NO_x emissions at local and global levels are a formidable set of environmental constraints and objectives that may require major breakthroughs such as: (i) variable cycle engines with high jet speeds at cruise and lower exhaust velocities at take-off and landing; (ii) novel aircraft configurations like flying wings, joined wings, V- or U-tails with shielding of noise and/or flush or buried engines. These developments that may be needed to meet (a) ever-stricter environmental standards must be compatible with (b) increased efficiency and economy since both enable the continuation of air traffic growth at the service of mobility.

In 2008, the EU decided to include aviation activities in the EU ETS [**EC, 2008, Directive 2008/101/EC**]. These emissions now form part of the EU's internal 20% greenhouse gas (GHG) emission reduction target for 2020. Based on national GHG emission reports to the United Nations Framework Convention on Climate Change, domestic aviation from the EU Member States accounts for less than 0.5% of total EU GHG emissions, whereas international aviation represents 3%, a relative share which is increasing [**EEA, 2014**]. One example is the ETS which is a cornerstone of the EU's policy to combat climate change and its key tool for reducing industrial greenhouse gas emissions cost-effectively. The ETS either incentivises CO_2 emission reductions within the sector or through the purchase of emission reductions in other sectors of the economy where abatement costs can be lower.

In addition to improving operational efficiency and achieving technological progress, the aviation community is putting significant efforts in promoting the use of sustainable alternative fuels that have a reduced carbon footprint compared to conventional jet fuel. However, hurdles (mainly economic) still exist to prevent a large-scale production. A complementary global MBM scheme would act as a policy tool that would allow for an immediate response to the need for cost-effectively stabilising the emissions for international aviation to meet its aspirational goal.

According to Assembly Resolution A39-3, paragraph 4, the role of a global MBM scheme is to complement a broader basket of measures to achieve the global aspirational goal (of carbon-neutral growth from 2020 onwards). Paragraph 5 of the Assembly Resolution decides to implement a global MBM scheme in the form of the Carbon Offsetting and Reduction Scheme for International Aviation (*CORSIA*) to address any annual increase in total CO_2 emissions from international civil aviation (i.e. civil aviation flights that depart in one country and arrive in a different country) above the 2020 levels, taking into account special circumstances and respective capabilities. The average level of CO_2 emissions from international aviation covered by the scheme between 2019 and 2020 represents the basis for carbon-neutral growth from 2020, against which emissions in future years are compared. In any year from 2021 when international aviation CO_2 emissions covered by the scheme exceed the average baseline emissions of 2019 and 2020, this difference represents the sector's offsetting requirements for that year.

As in paragraph 9 of the Assembly Resolution, the CORSIA is implemented in phases, starting with the participation of States voluntarily, followed by participation of all States except the States exempted from offsetting requirements, as follows:

- Pilot phase (from 2021 through 2023) and first phase (from 2024 through 2026) would apply to States that have volunteered to participate in the scheme; and
- Second phase (from 2027 through 2035) would apply to all States that have an individual share of international aviation activities in RTKs in the year 2018 above 0.5 per cent of total RTKs or whose cumulative share in the list of States from the highest to the lowest amount of RTKs reaches 90 per cent of total RTKs, except Least Developed Countries (LDCs), Small Island

Developing States (SIDS) and Landlocked Developing Countries (LLDCs) unless they volunteer to participate in this phase.

States that voluntarily decide to participate the CORSIA may join the scheme from the beginning of a given year and should notify ICAO of their decision to join by June 30 the preceding year. CORSIA would be the first global MBM scheme for a whole sector, and a major step to complement the efforts made by States in the context of the Paris Agreement. Action for the implementation of the global MBM scheme for international aviation from 2020 will start right after the Assembly.

The major environmental issues of aviation concern noise and emissions (Key Topic T4.1) that are the subject of different views in the literature (Key Topic T4.2). The prospect of emissions-free airport movements is related to battery technology (Key Topic T4.3).

The long-term sustainability of aviation may depend on the availability of alternative fuels (Key Topic T4.4). The atmospheric research contributes to minimising the weather and environmental effects of aviation (Key Topic T4.5).

KEY TOPIC T4.1 – REDUCTION OF NOISE AND EMISSIONS

Benchmarks

As a result of technological improvements, the noise footprint of new aircraft is at least 15% smaller than that of the aircraft they replace.

According to ICAO, aircraft being produced today are 75% quieter than those manufactured 50 years ago. In spite of technological and operational advances, many airports have responded to community pressure by introducing noise-related charges on aircraft. However, the introduction of noise-related charges is often not an effective means to reduce the exposure of local communities to airport noise. Noise-related charges do not drive the development of quieter aircraft nor their deployment to airports. Additionally, noise-related charges are often introduced without a proper airport noise management plan and are often based on criteria that are inconsistent across airports and lack transparency. Funds generated by such charges are also not always dedicated to noise alleviation and prevention measures. Furthermore, the additional financial burden they put on airlines and passengers has a negative impact on the local economy.

In 2001, the ICAO Assembly unanimously endorsed the ICAO Balanced Approach to Aircraft Noise Management by adopting Resolution A33-7. The core principle of the Balanced Approach is that the noise situation at each airport is unique and that there is no one-size-fits-all solution. The ICAO Balanced Approach, therefore, requires that all available options be evaluated to identify the most suitable measure or combination of measures to mitigate a specific noise problem.

New engine architectures

Preliminary studies to probe various technologies have already been conducted, or are being conducted, both for Ultra High Bypass Ratio engines and Open Rotors. These two technological tracks are both presumed to lower fuel consumption and to reduce noise emission (at least jet noise, since tonal noise, may dramatically increase for Open Rotors).

For instance, from 2008 to 2011, within the DREAM project (EC 7 framework program), preliminary campaigns were led to compare noise measurements and numerical simulations on some Open Rotor configurations. Computational Fluid Dynamic (CFD) and Computational AeroAcoustics (CAA) made by Onera (France) appeared to be in good agreement with the measurements performed by Tsagi (Russia).

Progress up-to-now/ Predictions up-to-2025/ Evolutionary progress up-to-2025

In 2014, ICAO adopted a new standard that will result in a reduction of 7 Effective Perceived Noise Decibels (EPNdB) compared to the current Chapter 4 Standard. The new standard will apply from 2018.

As a result of technological improvements, the noise footprint (85 dB(A) maximum sound pressure level contour) of new aircraft is up to 50% smaller than that of the aircraft they replace (Source: Lufthansa). Further design improvements such as blended wing body and engine shielding by fuselage and tailplane offer the potential to reduce perceived noise from aircraft by 65% by 2050 (Source: Sustainable Aviation). Airlines will be investing USD 4.5 trillion in newer and quieter aircraft over the next 20 years (Source: IATA). ICAO's final report to CAEP/8 meeting established the goals for four classes or categories of aircraft were as follows (Table 4.11):

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 4.11: 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 CleanSky Framework: In France for instance, Snecma's Hera test vehicle underwent preliminary testing in Onera's S1 wind tunnel in July 2013. Full-scale propeller tests were made in 2015.

Further new technological research programs have already been launched. Especially, it is worth mentioning COBRA, a new EU-Russia cooperation program that started in October 2013 and that is considered as the continuation of VITAL and DREAM. Actually, COBRA is dedicated to the consolidation of Ultra High Bypass Ration (UHBR) Contra-Rotating TurboFan (CRTF) that was once explored by Kuznetsov – one of the Russian partners – in the early 90s and further explored within VITAL. CRTFs associate two contra-rotating fans in a nacelle and thus appear as a kind of hybrid between turbofans and Open Rotors. CRTFs envisaged by COBRA strongly differ from those experimented with within the VITAL program and by the Russian engine manufacturer. Kuznetsov's NK-93 (BPR ~ 16.5) highlight the good behaviour in term of performance of this concept, but the design was made over more than 20 years ago without the current computational tools and free from present environmental constraints.

At the time being, indeed the first NK-93 full-scale tests showed that noise performances of such UHBR CRTFs were not so bad and that the combustion chamber has been up to now one of the most efficient among the Russian ones. Compared to VITAL, COBRA plans to explore a higher bypass ratio (BPR ~ 11 within VITAL) with the obligation to use a gearbox in order to reduce the fan speed. This reduction will directly impact the tip velocity and thus will allow the fan noise to be reduced. Within the COBRA project, the BPR investigated is from 15 to 25, according to the detailed specifications proposed by the partners in charge of this activity (Snecma and Kuznetsov).

A specific conception/optimization will be proposed by European research centres (Onera and DLR) and by Russian partners (CIAM, Kuznetsov, AEROSILA and MIPT). Both designs will be manufactured by COMOTI and tested at CIAM's C3-A test rig facility.

NASA/P&W Ultra High Bypass Turbofan Research

Under the Engine Validation of Noise and Emissions Reduction Technologies (EVNERT) task of the NASA Glenn Revolutionary Aero Space Engine Research (RASER) contract, which was sponsored by the NASA Quiet Aircraft Technology program, NASA and Pratt & Whitney (P&W) formed a collaborative partnership to develop an Ultra High Bypass engine demonstrator. The goal was to verify the potential advantages in reducing fuel burn, noise and emissions that could be achieved with an engine cycle having a fan to core flow bypass ratio of 13 and a fan pressure ratio of 1.3. P&W designed their engine, which they labelled the Geared Turbofan (GTF), with a geared Low-Pressure Core fan allowing the core and fan to operate at different speeds, thus optimizing the performance and reducing the complexity of the core.

NASA UHB Fan Noise Reduction Research

To help meet the aggressive N+1 noise reduction goal of 32 dB cumulative below the Stage 4 noise regulation, the SFW Project supported a high fidelity wind tunnel experiment of a scale model UHB turbofan-simulator to investigate the potential of two advanced noise reduction technologies, called Over-the-Rotor (OTR) metal foam acoustic treatment and Soft Vanes (SV) acoustically treated stator vanes, for the UHB engine cycle (Figure 4.100). 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.

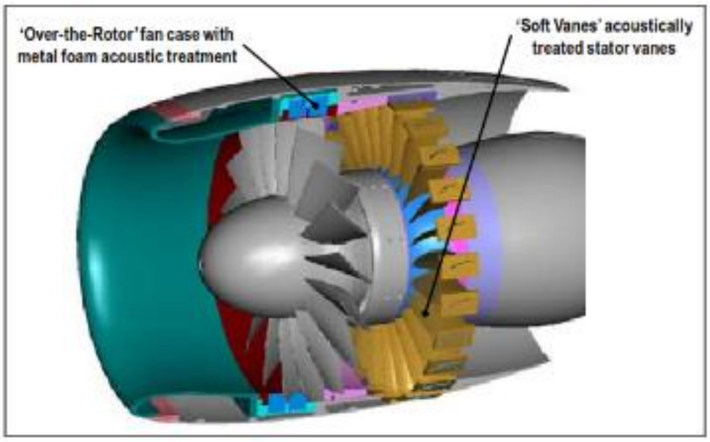


Figure 4.100: Illustration of the UHB Fan Model identifying the locations of two noise reduction technologies used during the NASA Ultra High Bypass Fan Noise Reduction Test, which were Over-the-Rotor acoustic treatment and Soft Stator Vanes.

The Over-the-Rotor acoustic treatment was designed to replace the traditional hardwall fan case and rub strip over the fan tip. The new design consisted of a 0.10" thick perforated hard plastic polymer flow surface with a 1.5" thick porous metal foam material behind it and contained within a steel shell which interfaced with the rest of the model hardware. The hard-plastic flow surface had 0.035" holes drilled into it resulting in a 20% open area and allowing the acoustic pressure disturbances to pass through into the metal foam liner behind it. The size and number of holes were designed to minimize the impact on the fan aerodynamic performance. The metal foam had a density of 6% to 8% (or 94% to 92% open area) with extremely small holes of approximately 100 pores per cubic inch of material. The metal foam presented a random and tortuous path to the incoming acoustic waves, forcing dissipation of the wave energy internally in the foam.

The design allows the local acoustic waves on the vane suction surface to penetrate into the vane's four internal chambers, where the acoustic energy would dissipate.

Possible or Predictable Breakthroughs

Ultra-HighBypass Ratio engines (UHBR) are being studied, but with very hard integration issues, since the fan diameter is even greater than that presently used. With this option, noise reduction would basically entail pushing the same technologies further than those presented above. However, it must be kept in mind that new noise sources could emerge from these more "open" engines, especially if traditional ones, such as fan and jet, are lowered. In this case, core machinery noise, such as compressor noise, turbine noise or even combustion noise would need to be considered. Currently, there is reasonable confidence that Open Rotors will be able to meet the strictest regulation of ICAO Annex 16 Chapter 14 in a few years. From a programmatic standpoint, the main framework for such integrated research is the CleanSky research program, which will allow the engine manufacturer Snecma to produce a demonstrator by the end of the decade. Through this platform, new noise technologies, such as 3D-optimized blade design and pylon blowing in order to strongly reduce the interaction of the pylon wake with the blades, will be demonstrated. Current liner-based technologies will probably be used less since they are both inefficient and impossible to insert into open architectures.

It is also worth mentioning that the most recent trends tend to locate these forthcoming Open Rotors (Figure 4.101) rearward, near the empennage, between two vertical stabilizers, both to gain from the masking effect for community and to increase comfort and safety for passengers. Currently, aircraft manufacturers have not yet chosen between the two competitive technologies of UHBR and Open Rotors, but this critical choice is considered imminent and was likely to arise before 2015. Neither the first nor the second technological route will be sufficient to meet the stringent new objectives defined by ACARE for 2050 (Figure 4.102).

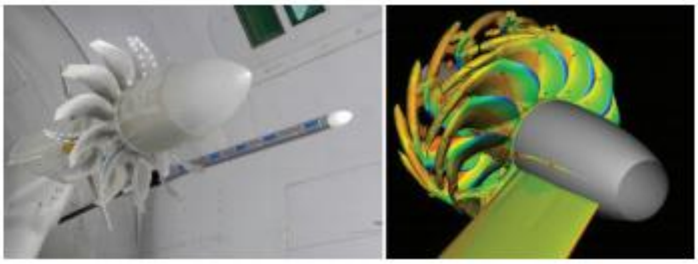


Figure 4.101: Open Rotor mounted on Hera vehicle (Snecma) and under test at the S1 Onera wind tunnel and the simulation of interactions between the two propellers (Onera)

It is generally assumed that though 2020 objectives will be reached through enforcing new Noise Abatement Procedures (NAP) in addition to NRTs, 2050 objectives will require a breakthrough in aircraft architectures. Clearly, these most silent configurations would then involve integrating engines into the aircraft fuselage, or architectures where the engines would be completely shielded. Once again, these future configurations would strongly reduce both fuel consumption – through a dramatic reduction of the drag – and noise, with masking effects. Succeeding to build up such a configuration is a huge challenge since it would involve fully reinventing the entire aircraft with unexplored aerodynamic effects and brand-new propulsion systems. In particular, these engines would ingest air flows with intense distortion of the boundary layer, an unfamiliar configuration that remains to be addressed by research. However, the greatest challenge is probably not technical but commercial and psychological. Before engaging in such developments, manufacturers need to convince airliners of the expected benefits and the latter need to accustom their customers to the idea of embarking on such new aircraft. These challenges go far beyond technical issues.

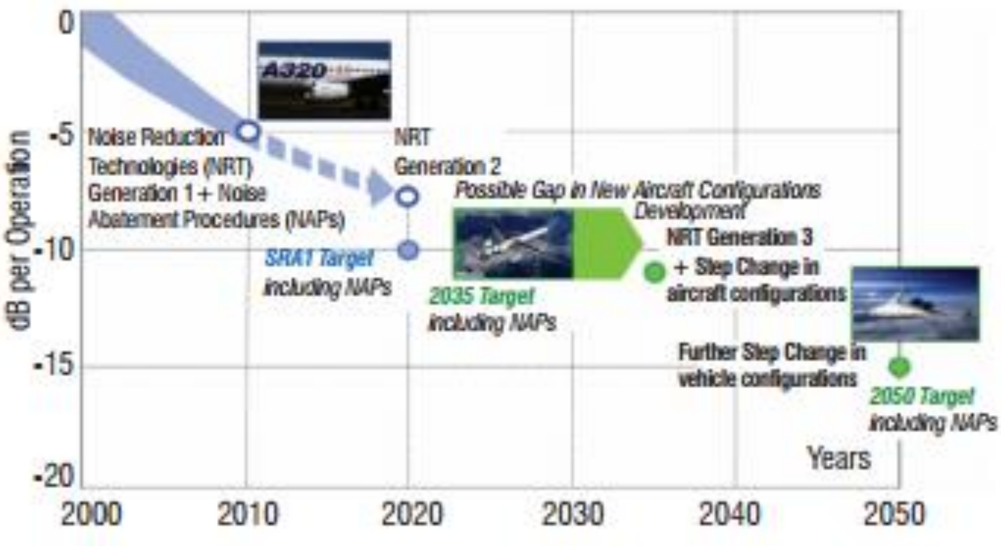


Figure 4.102: Further ACARE objectives for 2050

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 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.

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 the 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 of global warming and climate change. According to Schilling (2016)'s report, the objectives set by the aviation industry in 2009 cannot be met especially the long-term reduction goal of CO_2

emissions by 2050. AIRCAT project is a collaborative work of IATA and DLR to identify possible challenges, obstacles and roadblocks to the deployment of new technologies. They selected three aircraft designs of low-emissions concepts as battery-driven, hybrid wing body and strut-braced wing with open rotor design. In addition, analyse two types of low-carbon alternative fuels as drop-in solar jet fuel and natural liquid gas. Consequently, they assessed that the majority of emissions reductions necessary to meet the 2050 goal would have to come from low-carbon fuels and radically new fuels. Another study is coming with Hassan et al. (2017)'s criticism regarding the challenges. Hassan et al. (2017) studied the feasibility of the aviation goals on CO_2 emission reductions designated for 2050 and by considering 40 different scenarios they found that these goals are not feasible because of the high demand growth. Moreover, with medium or low demand growth coupled with high technology introduction rates and faster retirement of old aircraft they found that the goals are feasible. According to Jovanevic and Vracarevic (2016) especially rising travel demand constrained to perform a designated challenge. They studied the feasibility of global climate stabilization goals (70% reduction of CO_2 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 CO_2 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 a 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 the overall aircraft level. Finally, they found that with selected technologies in the study it was not likely to reach any of the goals. They proposed that for reaching the aforementioned goals of EU considering noise and NO_x goals radical approaches would be necessary for the airframe and the propulsion system. 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 2.5×10^9 tons of NO_x 17.6 billion tons of CO_2 was released. He asserted that NO_x is playing the most important role in the promotion of CO_2 assimilation and nutrient N and P in drainage should be used for fixing CO_2 and protecting global warming.

Alternative fuel usage is another option among researchers. However, according to (Noh et al. 2016) using alternative energy fuels has other research issues that should be met in future. (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 needs 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 was a number of vital reasons why significant climate policy for the transport sector was not being effectively developed at the EU supranational level and implemented in member states.

(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 on 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 the 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 an 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 the 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 the aerospace community. They demonstrated that exergy analysis and mapping exergy destruction would provide to the aerospace industry with the following six items. These were;

- "A consistent common currency to allow consistent accounting across subsystems;
- Loss-producing mechanisms can be readily mapped at the system level;
- Analysis space provides physically possible/meaningful bounds;
- Provides a foundation for robust and efficient optimization;
- Should produce the same result regardless of the 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 the FAA's vision of how a nation's aviation system would operate in 2025 and beyond. The NextGen initiative was established in 2003 in order to meet the challenges of the 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 the 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 hybrid and electric aircraft concepts were 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 the contour area.

Schwaiger and Wills (2016) proposed that cyclo-gyro propulsion can be used for vertical launch and had the 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 several 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, the scientometric approach is applied. Data is retrieved from the Web of Science database by using “aviation” and “noise” keywords in the Topic Sentence field. After a search, 461 publications are reached, and metadata of these publications downloaded in text format. Then, pre-processing is applied as a 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 Figure 4.103.

As can be seen in Figure 4.103 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 Figure 4.103, technology-related nodes are not revealed as expected. It is thought that selected keywords may affect this result.

An approach by consensus based on expert’s judgement, assessment of the TRL situation and results from the technology evaluation exercises have then been used to perform the 2015 progress assessment, coming up with updated progress achievement figures and formulating associated recommendations for future research. Recommended Phased Approach to meet ACARE Noise Goal #1 includes analysis of expected advances on noise reduction with Noise Reduction Technology 1 (NRT1) and NRT2, as well as the Noise Abatement Procedure, (Figure 4.9, 4.10).

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 9** "Reduction of Noise and Emissions" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.104 grounding on the results of the 1st year PARE report (PARE D1.1, 2018).

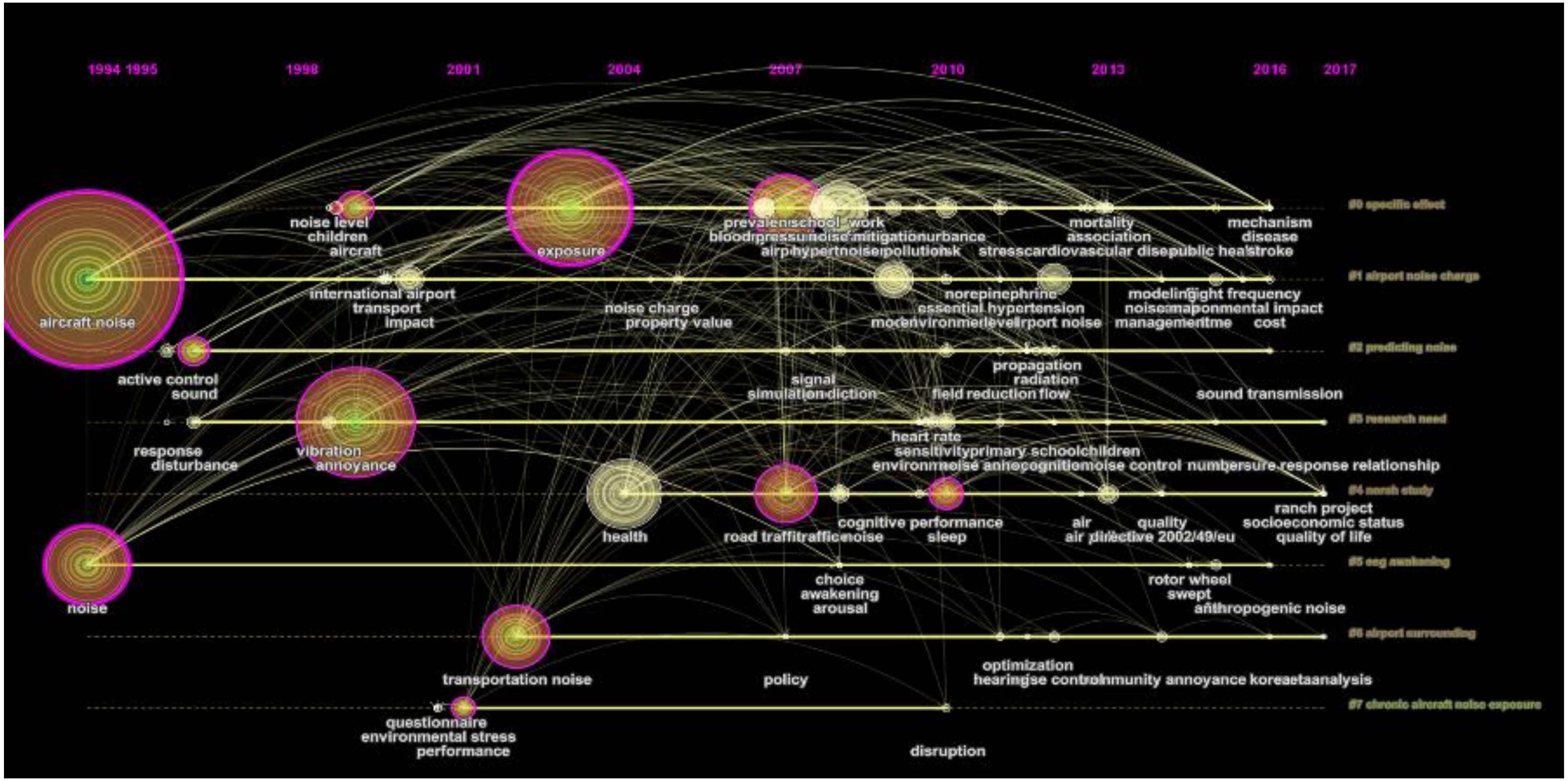
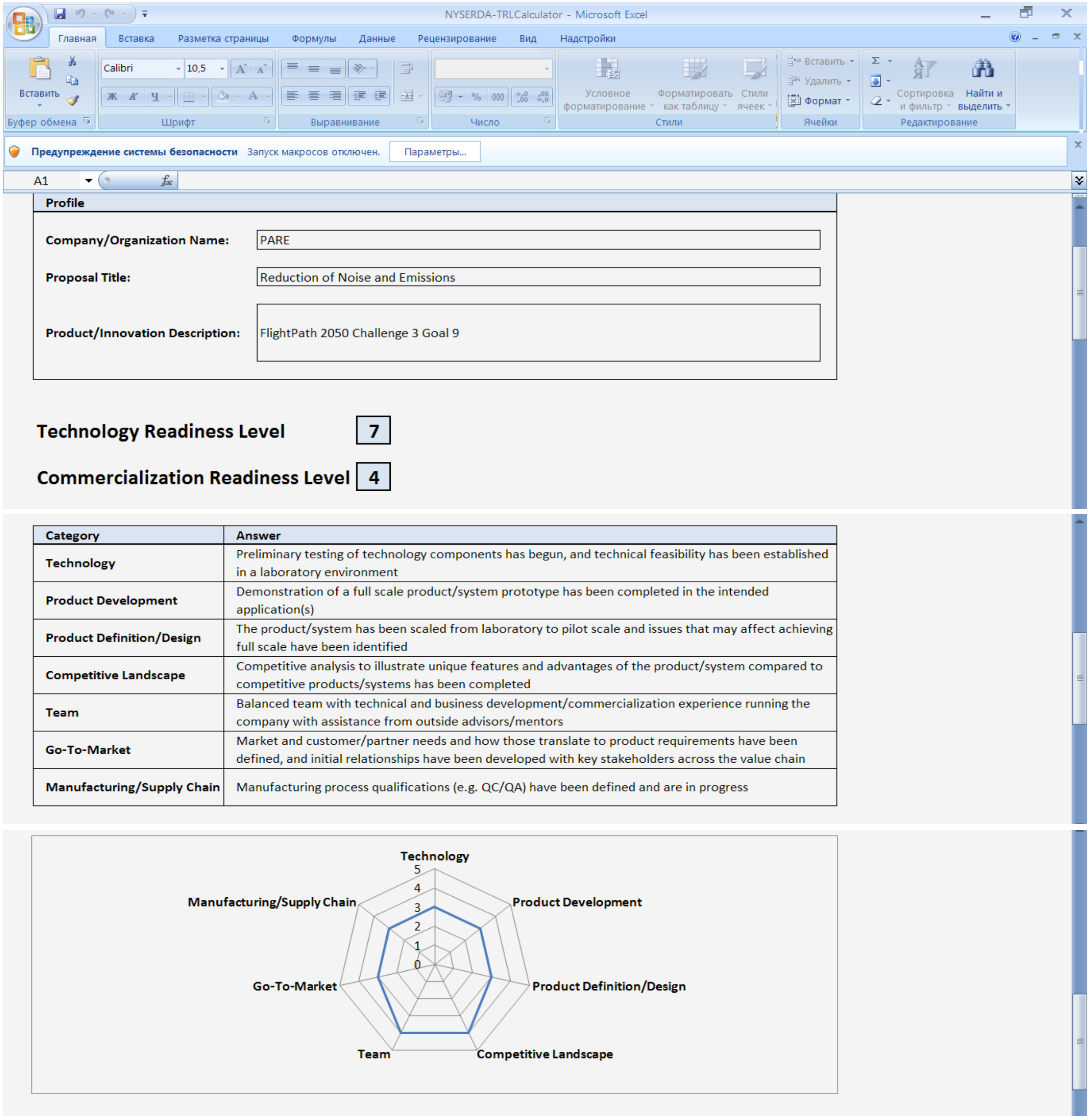


Figure 4.103: Timeline Demonstration of Noise Related Scholarly Publication


NYSERDA-TRLCalculator - Microsoft Excel

Profile

Company/Organization Name: PARE

Proposal Title: Reduction of Noise and Emissions

Product/Innovation Description: FlightPath 2050 Challenge 3 Goal 9

Technology Readiness Level 7

Commercialization Readiness Level 4

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Demonstration of a full scale product/system prototype has been completed in the intended application(s)
Product Definition/Design	The product/system has been scaled from laboratory to pilot scale and issues that may affect achieving full scale have been identified
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Market and customer/partner needs and how those translate to product requirements have been defined, and initial relationships have been developed with key stakeholders across the value chain
Manufacturing/Supply Chain	Manufacturing process qualifications (e.g. QC/QA) have been defined and are in progress

Figure 4.104: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 9** "Reduction of Noise and Emissions"

4.2 Emissions Free Taxying at Airports

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

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 sufficient traction power. Also infrastructure aspects with recharging facilities for a fleet of electric towing vehicles. At last, but not least, the coverage of the initial investment and operating cost. These must be seen in the context of lower environmental impact.

- Input:

- fuel spent and emissions associated with taxying at airports: worldwide and at specific airports
- 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 T4.2 – AIRCRAFT MOVEMENTS ARE EMISSIONS FREE WHEN TAXING

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 is the lead-acid and the nickel-cadmium battery.

Aircraft:

a. Internal engine starter generator (ESG) set
b. The auxiliary power unit (APU) which includes battery and super/ultra-capacitor
c. Flight control actuation, and a fault-tolerant Power Management and Distribution (PMAD)
d. Motor drive system

Other motorized movements at the airport:

a. Moving the aircraft from the gate to the starting position
b. Other motorized movements at the airport

Both technologies are long in the field and therefore technically very mature but suffer from insufficient energy density and cycle life. In order to meet the future requirements, substantial improvements in energy density, lifetime, cost and charging infrastructure are needed. The following Tables 4.12 – 4.15 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 4.12: Comparison of different types of battery chemistries [adapted from Gianfranco Pistoia, "Batteries for Portable Devices", Elsevier 2005]

	Battery manufacturer / *model nr.*	**Chemistry**	**Aircraft**	**System Voltage / V**	**Capacity / Ah**
1	Saft-*2758*	Ni-Cd	A320	24	23
2	Saft- *4059*	Ni-Cd	A340	24	40
3	Saft-*405 CH*	Ni-Cd	A330	24	40
4	Acme Aerospace Inc-263BA101-*2*	Fibre Ni-Cd (FNC)	B-777	24	47
5	Saft-*539 CH1*	Ni-Cd	B-737NG	24	53
6	Saft-*539 CH1*	Ni-Cd	B-767-400	24	53
7	Saft-*539 CH2*	Ni-Cd	A380	24	50
8	GS Yuasa *LVP-40-8-65*	Li-Ion	B-787	28.8	75
9	Saft-*40176-7*	Ni-Cd	B_747 x	24	40
10	Concorde *RG150-1*	VRLA	B-717	24	3.5
11	Marathon *Nacro 7-75M3-120*	Ni-Cd		8.4	75
12	Concorde *D8565/5-1*	SLA, lead acid	C-130	24	30
13	Concorde *D8565/11-1*	SLA, lead acid	C-141, F4	24	10

Table 4.13: Details of batteries used in different aircraft [Adapted from a. Aircraft batteries - current trend towards more electric aircraft IET Electr. Syst. Transp., 2017, 7, 2, 93-103]

	Li-ion*	**Ni-Cd****

Nominal cell voltage / V	3.20	1.20
Battery voltage / V	25.6	24.0
Capacity / Ah	45-55	23
Energy / Wh	1280	552
Typical battery cost / US $	~21.000	~6.500
Battery 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 4.14: Comparison of Li-ion and Ni-Cd aircraft grade batteries [Adapted from a. Aircraft batteries - current trend towards more electric aircraft IET Electr. Syst. Transp., 2017, 7, 2, 93-103]

	Cell level energy density Wh/kg	Cell level energy density Wh/L	Durability cycle life 100% DoD	Price estimate US$/ Wh	Power C-rate	Safety thermal runaway onset, °C	Voltage / V	Temperature range in ambient conditions °C
$LiCoO_2$	170-185	450-490	>500	0.31-0.46	1 C	170	3.6	-20 to 60
$LiFePO_4$ (EV/PHEV	90-125	130-300	>2.000	0.3-0.6	5 C cont. 10 C pulse	270	3.2	-20 to 60
$LiFePO_4$ (HEV)	80-108	200-240	>2.000	0.4-1.0	30 C cont. 50 C pulse	270	3.2	-20 to 60
NCM (HEV)	150	270-290	>1.500	0.5-0.9	20 C cont. 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	90-100	280	>1000	0.45-0.55	3-5 C cont.	255	3.8	-20 to 50

(EV/PHEV)								

Table 4.15: 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 4.16), 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.

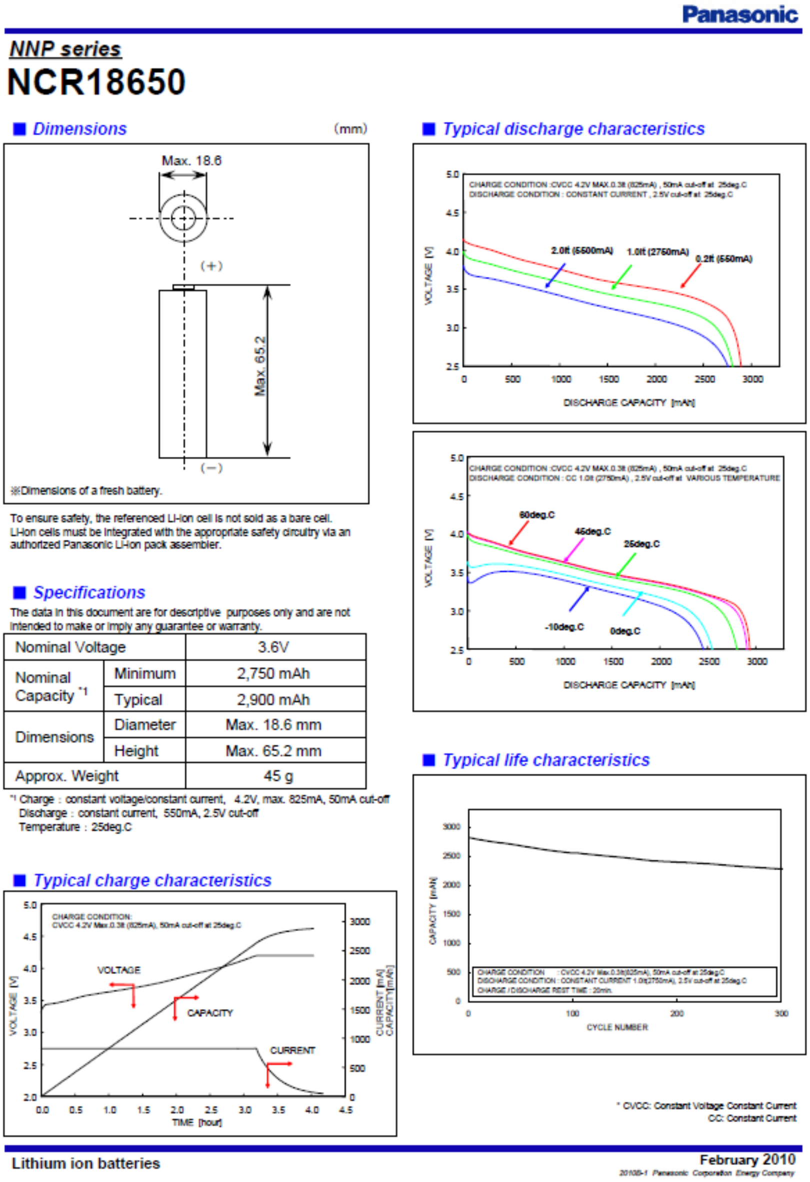
	Characteristics	Ni-Cd	Ni-MH	Lead Acid	Li-Ion
1	Cell voltage / V	1.25	1.25	2	3.7
2	Spec. energy density / Wh kg^{-1}	40-60	60-90	30-50	50-250
3	Energy density / Wh dm^{-3}	150-190	300-340	80-90	100-700
6	Cycle life	1000-1500	500-1000	200-300	300-10000

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 4.16: Comparison of different types of battery chemistries [adapted from Gianfranco Pistoia, "Batteries for Portable Devices", Elsevier 2005]

For the lithium-ion technology, it can be stated that these are mainly based on carbon as the anode and transition metal oxides, as well as phosphate as the cathode material. This combination and its variation have been the state of the art for years. Increase in the energy density could be mainly achieved by optimizing the cell production process. As an example of the state of the art from 2010 for an energy cell (Figure 4.105), the Panasonic NRC18650 should serve with an energy density of about 230 Wh/kg.

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. Table 4.17 shows an overview of various cells launched since 2010.



Panasonic

NNP series

NCR18650

■ Dimensions (mm)

Max. 18.6

(+)

Max. 65.2

(−)

※Dimensions of a fresh battery.

To ensure safety, the referenced Li-ion cell is not sold as a bare cell. Li-ion cells must be integrated with the appropriate safety circuitry via an authorized Panasonic Li-ion pack assembler.

■ Specifications

The data in this document are for descriptive purposes only and are not intended to make or imply any guarantee or warranty.

Nominal Voltage		3.6V
Nominal Capacity [*1]	Minimum	2,750 mAh
	Typical	2,900 mAh
Dimensions	Diameter	Max. 18.6 mm
	Height	Max. 65.2 mm
Approx. Weight		45 g

[*1] Charge : constant voltage/constant current, 4.2V, max. 825mA, 50mA cut-off
Discharge : constant current, 550mA, 2.5V cut-off
Temperature : 25deg.C

■ Typical charge characteristics

■ Typical discharge characteristics

■ Typical life characteristics

* CVCC: Constant Voltage Constant Current
CC: Constant Current

Lithium ion batteries

February 2010

Figure 4.105: Specification sheet for the Panasonic NRC 18650

Cell type	Manufacturer	Nominal	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	Molicel 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	Panasonic *UR18650Y*	3.7	2	43.3	-20 to 60	162	421	~300		Standard type of cell
$LiCoO_2$ and	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	Molicel *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	Panasonic *NCR18650*	3.6	2.25	45		180	~500	~1400	400	High power cell, cycle life I to 80% BOL

$LiCoO_2$ and NMC	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	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 *Nexelio nWH1*	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 4.17: 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 4.106) in which the energy density could be increased from 230 Wh/kg in ~2010 to 243 Wh/kg within the last years.

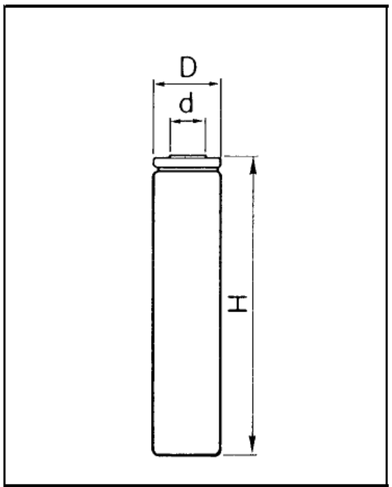
Nevertheless, even if the current (Li-Ion)- battery chemistry has proven itself, efforts are still to be made to increase the energy density as well as other key performance parameters to meet future requirements. In R&D advanced and post-lithium concepts are also considered, which are still far away from being commercialized.

Predictions up-to-2025 - Battery

In our opinion, especially the development of batteries for ground-operation-vehicles (e.g. towing tractors) is closely linked to the development of batteries for automotive electromobility. Of course, there are some differences in the technical requirements. For example, a long driving range is for an airport vehicle less important than high power (e.g.

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

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 4.106: Specification of the Panasonic NRC1865 battery

There are several deficiencies of the present-day lithium-ion batteries that, if remedied with suitable ease and cost parameters, would enable superior lithium-ion batteries that could open new applications and expand the market for present ones. First, it is important to consider certain market factors that will have important ramifications on cost, material availability, and needed technology improvements to enable mass production of different cell types and sizes. The market pull is strongly acting on lithium-ion battery manufacturers as application companies and governments around the world are asking for increased capacity and energy with a lower cost to fulfil the needs of greenhouse gas reductions through the implementation of electric vehicles of all types to replace petroleum and energy storage. So that intermittent renewable energy sources such as wind and solar can replace coal and natural gas fuels for energy production. The cost element is particularly important, for example, for motive power applications, e.g. for plug-in hybrid vehicles (PHEV) and battery electric vehicles (BEV). Recent estimates place the cost of producing lithium-ion cells is as low as $145 per kWh and the cost of a battery pack as low as $190 per kWh.

[http://www.greencarreports.com/news/1103667_electric-car-battery-costs-tesla-190-per-kwh-for-pack-gm-145-for-cells.]

The second area of major production possibility is that of energy storage in connection with stabilization and storage for the electric grid. This area is driven as much by the requirements of government regulations and incentives to enable renewable energy sources such as solar and wind generation, which are inherently intermittent, to fit the demands of electrical utility producers and users.

Besides, the cost is a very important driver for use of lithium-ion, but some applications such as frequency stabilization are not as cost-sensitive. If lithium-ion batteries are adopted for these applications, great demands will be placed on the availability of materials, especially lithium carbonate. To consider the likelihood of specific energy improvements in lithium-ion batteries we need to consider the limitations that exist now *[Source: G. E. Blomgren, J. Electrochem. Soc., 2017, 164, 1, A5019].*

Table 4.18 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

Location of Deficiency	Deficiency	Possible remedy
		cycling, dissolution of transition metal ions
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 4.18: Deficiencies of present lithium ion batteries and possible remedies [Source: G. E. Blomgren, J. Electrochem. Soc., 2017, 164, 1, A5019]

Evolutionary Progress up-to-2050- Battery

The history of lithium batteries is not that old, in contrast to fuel cells that have been described by Grove the first time in 1839. In the last 40 years, two new battery systems, Li-Ion and Ni/MeH, have not only dominated the portable electronics business but in many ways enabled it. They are now beginning to do the same for transportation, and Li-Ion has entered the electric grid market.

These advances have all been based on the concept of intercalation reactions. Now, the question that arises is how much further can intercalation chemistry be pushed? At a minimum, these cells will almost certainly displace Ni/Cd in consumer applications, as cadmium-based cells are banned from sale. There is still much room for improvement in the storage capability of Li-Íon cells.

- There is much dead weight and volume in today's batteries and supercapacitors. Also, the full capability of the active materials has not been attained. For example, the volumetric energy density of Li-ion batteries has increased from 250 to 680 Wh/L over the last decade.
- There is no reason to believe that the energy density can´t be further increased, possibly even as far as 50% on both volumetric and gravimetric basis within the next ten years. For almost all applications, the volumetric energy density is much more important than the gravimetric one.

However, further improvements will need significant changes in the materials used. One measure is to switch from lithium to magnesium. However, much effort will be needed to make a successful magnesium battery, including an anode, an electrolyte but most importantly a high-energy cathode. The beginnings of such cells will be accomplished within ten years, but without significant breakthroughs, it will probably not go commercial until 2030. Within ten years, the carbon electrode will have been replaced by metal alloy systems, perhaps tin or silicon-based. There is a finite probability that pure metals will be used in some liquid electrolyte cells by 2030. They find application today in all solid-state thin-film cells.

Related to conversion reactions 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.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 10** "Emissions Free Taxying at Airports" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.107 grounding on the results of the 1st year PARE report (PARE D1.1, 2018).

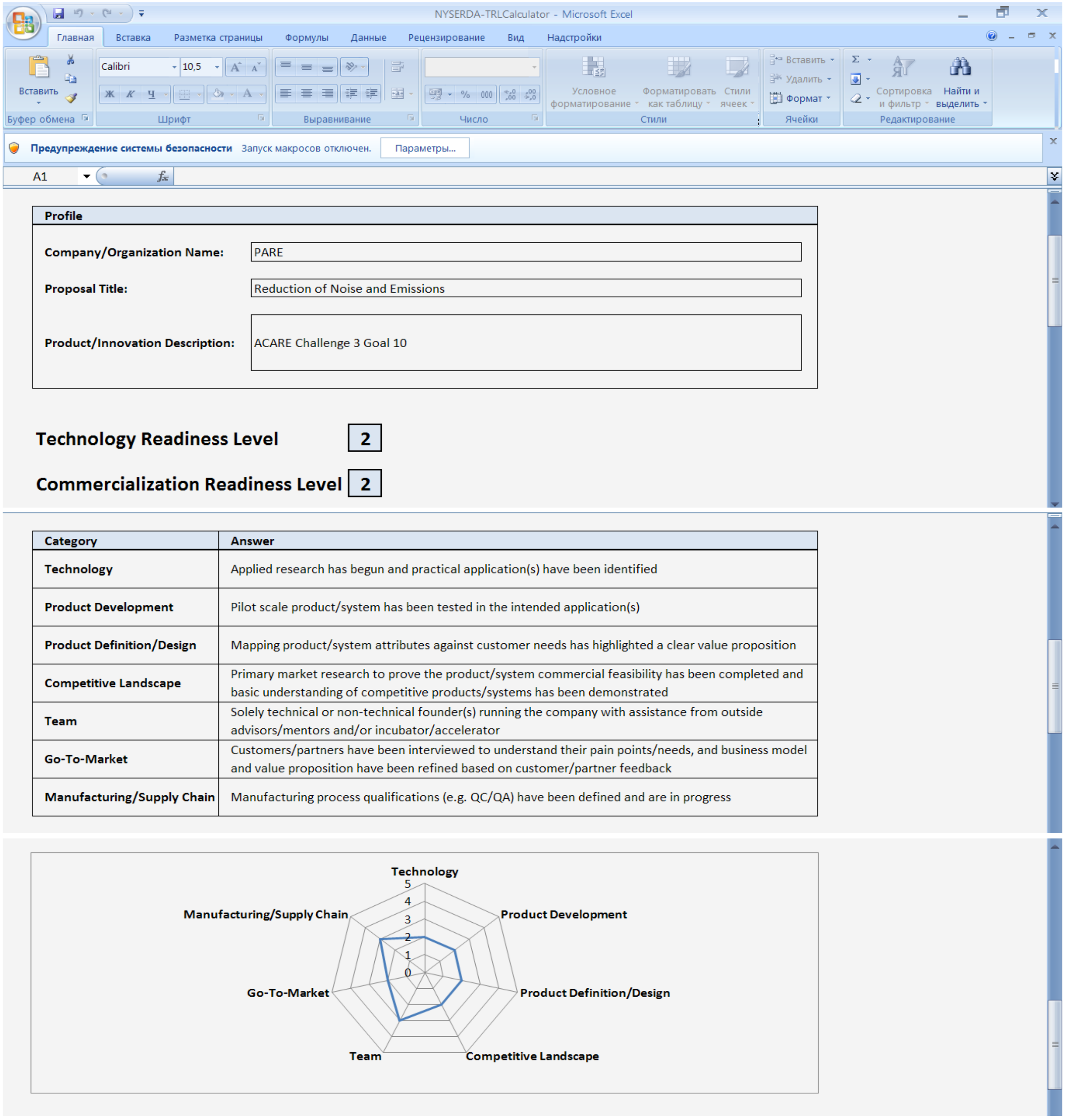


Figure 4.107: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 10** "Emissions Free Taxying at Airports"

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 T4.3 – Batteries for the More Electric Aircraft (MEA)

1) Requirements for Aircraft Grade Batteries

Competition in the aircraft industry market and global warming has driven the industry to think along economic and environmental lines. This has resulted in the emergence of a more electric aircraft (MEA) concept, providing for the utilization of electric power for all non-propulsive systems.

Traditionally these non-propulsive systems are driven by a combination of different secondary power sources such as hydraulic, pneumatic, mechanical and electrical. Recent technological advances in the field of power electronics, fault-tolerant architecture, electro-hydrostatic actuators, flight control systems, high-density electric motors, power generation and conversion systems have ushered the era of the *MEA*. This trend is accelerating, as aircraft manufacturers collaborate with their suppliers to design new systems and implement new electrical-intensive architectures. Adoption of the *MEA* concept is seen as a critical enabler for the aircraft industry to unlock significant improvements in terms of aircraft weight, fuel consumption, aircraft noise, total life cycle costs, maintainability and aircraft reliability.

The tremendous increase in the power demand of aircraft, especially in the last two decades, coupled with advancement in battery materials and technology has led to the development of many aircraft-grade battery systems with high energy density (more than 100 Wh/kg) and low-temperature capability with following key trades:

- To deliver power reliably and be certifiable safe
- To be lightweight
- To have a consistent power output over their operating environment
- To have a reasonably long life.

A small size, high energy density battery (Table 4.19) 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]

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 4.19: Comparison of different cell chemistries used in aeronautics

2) Types of aircraft batteries

Only vented Pb-acid batteries were in use in aircraft until the 1950s. In the late 1950s, military aircraft started using vented Ni-Cd due to higher low-temperature capability, which was adopted by commercial aircraft. The use of alternative battery chemistries like Ag-Zn was discontinued because of high costs and poor reliability. From the late 1960s, the development of sealed Ni-Cd batteries, followed by sealed Pb-acid batteries in the late 1970s started for aircraft application, in which maintainability and reliability have been improved significantly. Ultra-low maintenance Ni-Cd batteries were developed by *SAFT* and *Marathon Norco* since the mid-80s, replacing the conventional vented Ni-Cd batteries.

The most common voltage rating for main aircraft batteries is 24V, as capacities are available between 23 and 75Ah. The number of batteries installed in the aircraft depends on the system architecture, e.g. the Airbus A380 has a complex architecture requiring three 24 V, 50 Ah Ni-Cd batteries. A fourth 50 Ah battery is dedicated to APU starting. The total weight of the batteries is about 210 kg.

The life duration of an aircraft battery depends on various factors such as tt number of operating hours, ambient temperature, start frequency and on-board charge. It is therefore difficult to determine in advance how long the expected life of a battery will be in the real

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

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

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 4.20: Details of batteries used in different aircraft

Li-ion cells comprise sensitive electrochemistry which needs a detailed knowledge of its characteristics to allow its benefits to be exploited fully while ensuring maximum safety. We are likely to see further improvements in Li-ion performance as new electrode materials; electrolyte compositions and cell geometries are under research. Nanomaterials now being developed will also have a role to play. Nevertheless, Li-ion batteries are not currently envisaged as retrofit solutions, so Ni-Cd and Pb-acid batteries still have many years of work ahead of them.

Furthermore, many manufacturers include the Li-ion battery system with proper integrated battery management (BMS) and safety monitoring system, which are commercially available, e.g. the Li-ion battery with $LiFePO_4$-cell chemistry by *EaglePicher Technologies*.

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

3) Life Cycle Management – Recycling

In general, the same processes used to recycle automotive batteries are used to recycle aircraft batteries.[2]

A serious issue is related to the fact that the lithium battery market is in continuous evolution with the advent of many different new chemistries. Further, in addition to the rechargeable Li-ion batteries, also primary lithium batteries, using cathodes such as manganese oxide or thionyl and sulfuryl chloride, are still in the market and they may arrive at the recycling plant as well. Finally, also the electrolyte may widely change, passing from a variety of liquid organic solutions to polymer membranes. Clearly, this high diversity makes it difficult to develop a universally valid recycling process, as well as affecting its economics, since the new chemistries may not involve components worth being recovered.[3]

Indeed, the European Commission has mandated a Battery and Accumulator Directive, which imposes to the state members the following targets: [4]

[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

- A 45% collection rate for waste-portable batteries to be met by 2016. A recycling efficiency to ensure that a high proportion of the weight of waste batteries is recycled, this including 65% of lead-acid, 75% of nickel-cadmium, and 50% of "other waste batteries," the latter likely referring to lithium batteries.

Considering the present low economic value, these targets can be met only if subsidies are provided, usually adding a tax to each manufactured battery, as indeed is the case. Under this scheme, battery recycling plants are now operating in Europe (e.g., *Batrec* in Switzerland, *Umicore* in Belgium, and *SNAM* and *Recupyl* in France) to honour the mandate.

Recycling plants are also in force under different schemes in the US (e.g., *Toxco*) and in Japan (e.g., *Sony* and *SumitomoMetal*). Due to the still scarce production of Li-ion batteries of EV types, the recycling is for the moment limited to the portable ones.

However, EV battery recycling is expected to gain quite a significant importance in the years to come.

4) Risks Related to (Li-ion) Batteries in Aircraft

Due to the use of certain chemical compounds in combination with high energy densities and the use of control electronics (potential of a technical defect) required for secondary batteries, Li-ion batteries are associated with specific potential hazards which need to be taken into special consideration concerning safety. Spectacular incidents have raised public awareness of potential problems associated with Li-ion batteries.

- On 3 September 2010, UPS Airlines flight 6, a Boeing 747-400, crashed close to Dubai International Airport on its way to Cologne Bonn Airport, leaving two crew members dead. The crash had been caused by fire in the cargo area which contained lithium ion and lithium metal batteries.

- After a Boeing 787 coming from Japan had landed in Boston/US on 7 January 2013, fire broke out, caused by the thermal runaway of a Li-ion battery. As a consequence, the US-*Federal Aviation AgencyFAA* has mandated to install a casing for the battery to contain/extinguish the fire (Figure 4.108):

- On 12 July 2013, a non-rechargeable lithium metal battery in an ELT (emergency locator transmitter) of a Boeing 787 at London Heathrow Airport caught fire.

Figure 4.108: Boeing-787 relaunched the Li-ion battery system with the new design, adding an extra weight of 68kg to the weight of the airplane

It is characteristic of a battery that it releases chemically stored energy in the form of electric energy in the course of the discharging process. In case of a "thermal runaway", the entire energy is not released as electrical energy in a controlled manner, but uncontrollably in the form of thermal energy. In case of such a failure, the thermal energy released by a lithium-ion battery maybe 7 to 11 times higher than the energy stored electrically. The produced heat accelerates the reaction, resulting in a critical overheating of the battery.

Besides, cathode materials may disintegrate at high temperatures. This reaction also produces heat (exothermic reaction) and releases bound oxygen; when a fire breaks out, the thus released oxygen makes it difficult to control the fire. It is even impossible to extinguish such a fire using conventional fire extinguishing methods.

Causes of battery fires:

- Improper handling;
- Mechanical damage;
- Secondary thermal stress;
- External short circuit, Internal short circuit caused by a cell failure or crash;
- Overcharge, Over-discharge and exhaustive discharge;
- Cooling system defect (large-scale batteries);
- Counterfeit lithium-ion batteries and chargers.

5) Threats Regarding Aircraft Batteries

5.1) Permanently installed batteries[5]

There are several potential threats that can be associated with aircraft batteries (Figure 4.109), their distribution networks and their charging and monitoring systems:

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

Figure 4.109: Use of batteries in a typical aircraft

- Battery Leakage. Overfilling a wet cell battery can cause leakage. Likewise, damage to the battery case caused by mishandling, overcharging or freezing can result in leakage.
- Battery Internal Failure or Short Circuit. Manufacturing defects or inappropriate handling can result in internal failures.
- Battery Overcharging. Batteries can be overcharged due to faulty charging equipment or inappropriate maintenance practices.
- Excessive Battery Charging/ Discharging Rate. Some battery types are vulnerable to high rates of charge or discharge.
- Battery Bus Fault or Fire. A Battery Bus Bar is "hot" - it cannot be electrically isolated from the source battery without physically removing the battery. [6]

As a consequence, the following preventive measures should be undertaken:

- Containment of thermal effect;
- High standard electronic protection against overheat (overcurrent, overvoltage, short circuits);
- The specific choice of battery structural material and design;
- Battery management system with a cooling system;
- Mitigation of pressure release effect;
- Venting areas within the battery/module;
- Specific venting outside the battery/aircraft when relevant;

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

- High robustness to shocks (handling) and ageing;
- Adequate integration in the Aircraft.

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

By accident of intentionally triggered thermal runaway of Li-ion cells occur due to devices carried by passengers in an aircraft cabin (Figure 4.110).

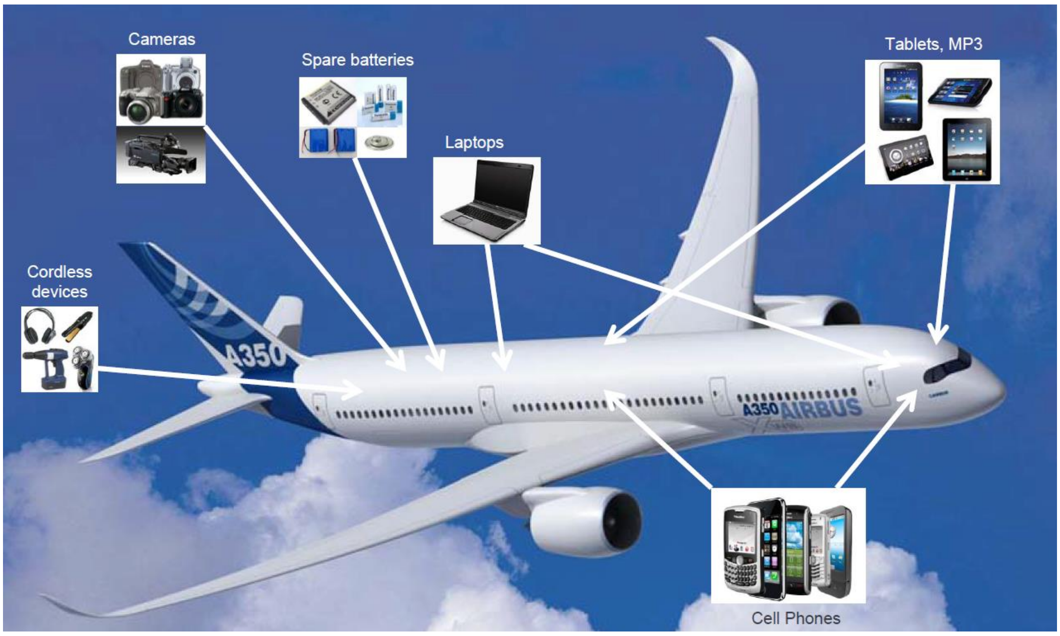


Figure 4.110: Batteries in the cabin of an airliner

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

Batteries in cargo cabin can cause safety risks also, Figure 4.111.

Shipping lithium batteries have also caused havoc in the airline cargo industry. In the last years, the *U.S. Postal Service* banned the shipment of lithium batteries until the ruling was reversed in November. *Cathay Pacific* and *British Airways* recently discussed banning the shipment of any related Li-ion battery devices in their cargo holds.

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

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

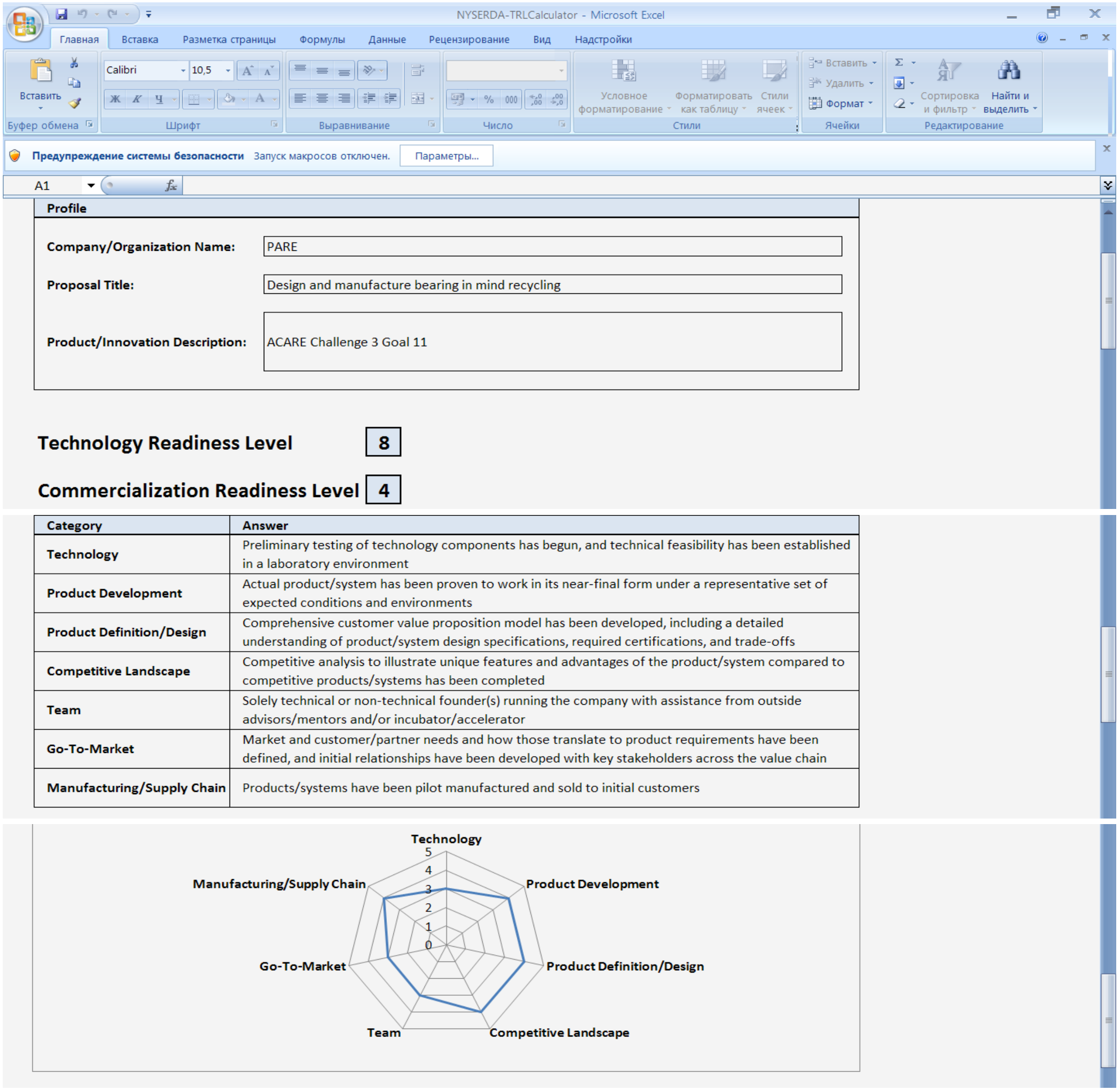
There is so much concern in the industry over onboard fires related to lithium-ion that the *FAA* released a Safety Alert for Operators dated Oct. 8, 2010. The title is "Risks in Transporting Lithium Batteries in Cargo by Aircraft."

Figure 4.111: Cargo with batteries that can cause safety risks

Furthermore, cargo areas are not accessible for direct firefighting and *Halon 1301*, used as a fire extinguishing agent in cargo holds or engines, is insufficient to stop the thermal runaway and prevent propagation to adjacent cells.

Recycling of aircraft parts depends mostly on the materials used and also on the fabrication process. The choice of materials for an aircraft is subject to a considerable set of constraints related to performance, weight, availability, cost, ease of manufacture and maintenance, durability and resistance to hostile environments. Adding the recycling ability is an additional constraint which can bring benefits in several of other areas; it may require consideration of materials not previously used in the aerospace industry and take advantage in the major progress made synthetizing new substances with tailor-made properties (graphene). There is a need for effective materials extraction and separation technologies, worthwhile end-use applications for the recovered materials as well as an attractive business model for aircraft recyclers. Only when all of these conditions are united can the aircraft recycling industry truly take off in Europe.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 11** "Design and manufacture bearing in mind recycling" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.112 grounding on the results of the 1st year PARE report (PARE D1.1, 2018).



Profile

Company/Organization Name: PARE

Proposal Title: Design and manufacture bearing in mind recycling

Product/Innovation Description: ACARE Challenge 3 Goal 11

Technology Readiness Level 8

Commercialization Readiness Level 4

Category	Answer
Technology	Preliminary testing of technology components has begun, and technical feasibility has been established in a laboratory environment
Product Development	Actual product/system has been proven to work in its near-final form under a representative set of expected conditions and environments
Product Definition/Design	Comprehensive customer value proposition model has been developed, including a detailed understanding of product/system design specifications, required certifications, and trade-offs
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Solely technical or non-technical founder(s) running the company with assistance from outside advisors/mentors and/or incubator/accelerator
Go-To-Market	Market and customer/partner needs and how those translate to product requirements have been defined, and initial relationships have been developed with key stakeholders across the value chain
Manufacturing/Supply Chain	Products/systems have been pilot manufactured and sold to initial customers

Figure 4.112: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 11** "Design and manufacture bearing in mind recycling"

4.4 Sustainable Alternative Fuel Sources

Flightpath 2050 goal 12: "Europe is established as a centre of excellence for sustainable alternative fuels, including those for aviation, based on a strong European energy policy.

The supply of fuel alternative to kerosene is subject to major efforts by large consumers like the U.S. Air Force. The consumer base is more diversified in the airline industry, but it is no less important due to a large number of flight hours. Although airlines have been willing to test new fuels a coordinated effort must be done far upstream to: (i) consider a variety of sources of fuel, that do not interfere with food production and whose environmental impact is neutral or positive (waste disposal); (ii) establish the technical feasibility to meet all applicable quality and safety standards and certification requirements; (iii) assess the economic and environmental feasibility of large-scale sustained production, distribution and use.

For example, hydrogen is a clean fuel that produces only water vapour by combustion. However, the quantities produced, and altitudes should be considered as for contrails. Hydrogen has a low volume power density and requires cryogenic conditions; water is an abundant source of hydrogen but its separation by hydrolysis is energy consuming. At the opposite extreme, some algae have high yields per unit area of culture; the full processing chain up to flight grade fuel needs to be considered. In between other options exist, making multiple sources of aviation fuel all the more desirable.

The Key Topic (T4.4) is thus the availability and sustainability of alternative fuel sources.

KEY TOPIC T4.4 – Sustainable Alternative Fuel Sources

The European Commission, Airbus, and high-level representatives of the Aviation and Biofuel producers' industries, launched in 2011 the European Advanced Biofuels Flightpath. This action is scheduled to achieve 2 million tons of sustainable biofuels used in the EU civil aviation sector by the year 2020. The overview of objectives, tasks, and milestones of this Flight Path[9] is shown in Table 4.21.

The supply of fuel alternative to kerosene is subject to major efforts by large consumers like the U.S. Air Force. The consumer base is more diversified in the airline industry, but it is no less important due to a large number of flight hours. Although airlines have been willing to test new fuels a coordinated effort must be done far upstream to: (i) consider a variety of sources of fuel, that do not interfere with food production and whose environmental impact is neutral or positive (waste disposal); (ii) establish the technical feasibility to meet all applicable quality and safety standards and certification requirements; (iii) assess the economic and environmental feasibility of large-scale sustained production, distribution and use.

[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 4.21: Objectives, tasks, and milestones of European Advanced Biofuels Flightpath

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.

Searching fuels alternative to kerosene is a subject of main efforts of the large consumers, such as USA Air Forces. The customer base is more diversified in the airlines' industry, but it is no less important due to the great number of flight hours. Although the airlines are ready to test the new fuel types, coordinated efforts shall be in advance undertaken, in order to:

1. Examine the variety of alternative fuels sources that are not intersected with food production, and the environmental effects of which are neutral or positive (elimination of waste).
2. Determine the technical feasibility of complying with all existing quality and safety standards and certification requirements.
3. Appraise the economic and environmental feasibility study of large-scale stable production, distribution and consumption.

For example, the hydrogen is a pollution-free fuel, during combustion of which only aqueous vapour is produced. However, the quantity of vapour generation and the altitudes concerning the appearance of condensation trails shall be taken into account. The hydrogen has a low power-to-weight ratio and requires cryogenic conditions; the water is an inexhaustible source of hydrogen, but its release from the water by hydrolysis requires lots of energy. The opposite extreme – some algae provide high output of production per cultivation unit area. It is necessary to consider the complete processing chain until deriving usable aviation fuel. Between these two extremes, there are other variants of provisioning aviation fuel sources, much more preferable.

The alternative types of fuels for aviation with less carbon intensity have been considered by many countries, both from the viewpoint of potential usefulness for the environment and delivery safety precautions [Kahn Ribeiro S., et al., 2007]. The alternative types of fuels are also a subject of ICAO's attention. In the Conference regarding the aviation and the alternative types of fuels (CAAF) 2009 a global base was established for developing the alternative types of fuels. The examples of fuels alternative to the traditional jet fuel (mineral kerosene), that were investigated in the effort [Grote M., Williams I., Preston J., 2014] are as follows:

– liquefied hydrogen (LH_2);

– methane;

– methanol;

– ethyl alcohol, ethanol;

– biodiesel (dimethyl ethers) based on retreatment of vegetable oils and fats;

– atomic energy;

– synthetical paraffine kerosene (SPK);

– Fischere-Tropsch (F-T) process, based on the retreatment of raw materials, such as biomass, natural gas or coal;

– hydrotreating (including hydrogenation, hydro-cracking and hydraulic cleaning, especially within the framework of oil refining) of vegetable oils and fats with hydraulically treated renewable reagent (HRJ). Sometimes the renewable reagent is referred to as bio-SPK or hydro retreated compound ethers and fatty acids (HEFA).

As it was found, the majority of variants from this list at present are not suitable for different reasons: heavy expenses, absence of infrastructure for fuel production and delivery, increased fuel tanks requiring greater fuselage volumes, which results in increase of the weight and the resistance, low energy density, safety problems [Lee, D.S., et al., 2010; Allen, C., et al., 2012; FAA, 2011].

Taking into consideration the growing ecological and energy problems during the last decade, the aviation industry has involved significant resources for developing stable alternative types of fuel that may promote the achievement of coordinated political objectives oriented to the diversification of electrical power supply, agriculture support and combating climate change.

The International Committee on fuel specification has developed a standard process [ASTM International, 2014], in order to check the suitability of the stable alternative types of fuels taking into account the requirements of existing systems and infrastructures. As a result, at the present, three ways of alternative fuel production are approved for using in commercial aviation, and they are included in the new alternative fuel standard [ASTM International, 2015]. Among these are:

– fuel based on the hydraulic treatment of vegetable oils and animal fats, such as hydrotreated compound ethers and fatty acids / hydrotreated vegetable oils (HEFA / HVO);

– Fischere-Tropsch fuel derived from biomass (the biomass down to BTL liquid);

– synthetic alisoparaffin fuels derived from sugars.

The first two fuels are approved for blending with traditional jet fuel in proportion up to 50 %, whereas the blending proportions of the synthetical isoparaffins are limited to 10 %.

On the short-term horizon, it can be provided more quantity of biofuel for aviation if the biodiesel will receive authorization for application in aviation. In spite of the fact that the biodiesel does not apply with the aviation requirements and requires further treatment for producing equivalent jet fuel, it can be potentially used in aviation in case of low blending proportions (till 10 %) with conventional jet fuel [EASA, EEA, EUROCONTROL, 2016].

Meanwhile, in connection with the expected oil price growth, ecologic requirement strengthening regarding the noxious emissions, as well as the eagerness to decrease the dependency on oil, the civil aviation in the developed countries directs its look to the alternative types of fuels.

The leading aircraft producers and airlines in these countries have already made a bid for biofuel, which it seems practical to be produced from different sorts of biomass and organic residues. The advantages of the aviation biofuel are the fact that its application is not related to changes in the existing engines and the fuel infrastructure. The carbon dioxide escaped in the course of burning is compensated by the quantity of carbon dioxide absorbed by the biomass from the atmosphere during vegetation. However, the energy expenditure for growing, transportation and processing of the biomass decreases this effect. Besides that, the expenditure of freshwater and agriculturally used areas for producing biofuel at a time when the best part of the global population faces the problems with food provision draws criticism. Nevertheless, the effect of compensating the carbon dioxide emissions at the expense of using the second-generation biofuels can make up 80 %. The International Air Transport Association (IATA) puts forward an objective of reaching the ratio of using the new generation biofuels in 2020 at the level of 6 %.

The western certification centres have approved the method of producing aviation kerosene from biomass (biomass-to-liquid) using the Fischere-Tropsch process, and later the method of producing biofuel from vegetable oil was approved. Under consideration are also other processes, by means of which production of biofuel is possible. Such a certification allows for airlines using biofuels on passenger flights in proportion with the conventional kerosene up to 50 %.

Already more than 1600 passenger flights with the use of biofuels (a mixture of biofuel and conventional kerosene) have taken place in the world. It can be expected that within the forecast period the developed countries will actively promote the implementation of biofuels in the aviation industry using sometimes provocative and forbidden financial mechanisms. The systems of emission trading will gain widespread. Thanks to these tools it will be possible to bring down the price of biofuel in comparison with the traditional fuel. In the European emission trading system (ETS) the CO_2originating from burning the ecologically friendly biofuels is not taken into account.

The hydrogen is also considered as an advanced alternative energy source for the aviation industry. It has thrice bigger energetic potential than the kerosene, however, even in the liquid state, it requires four times greater volume than the kerosene. In the process of its firing into the engine, the CO_2 is not generated, as well the NO_x emissions decrease. Also, it can be used in fuel cells for generating electric energy on the aircraft board. The problems of using the hydrogen as an aviation fuel are related, on the one hand, with technological difficulties during its transportation and storage, and on the other hand, with energy consumption of its production. The mass production of hydrogen, including in liquid state, is possible by using nuclear power engineering (in the future - thermonuclear reaction). It is expected that within the forecast period the hydrogen will not obtain a wide circulation in the aviation industry. However, the hydrogen is justifiably considered as an energy carrier of the future.

For some regions of Russia of current interest is the use of aviation condensed fuel that is produced from the oil-dissolved gas. Those are the regions where the substantial stocks of condensed fuel up to now are fired in torches on the oil deposits. Using this fuel will permit to solve the problem of securing aviation fuel into the outlying northern regions of the country. According to the program "Energy strategy – 2030" the maximally complete utilization and saving of the oil-dissolved gas resources is one of the strategic objectives of the oil complex industry. The strategy foresees that as late as at the end of the first stage of its realization 95 % of the extracted oil-dissolved gas will be efficiently used.

The Rolls-Royce Company carries out active investigations for evaluating the economically viable alternative types of fuels. In February 2008 R-R has joined with Airbus and Shell for testing the A380 aircraft flying with 40/60 mixture of GTL and kerosene (the GTL or gas-liquid) is are duction process of converting the natural gas or other gaseous hydrocarbons into more heavy hydrocarbons. The gases enriched with methane are converted to liquid fuel through the synthesis gas ($CO+H_2$) as an intermediate product by using the Fischere-Tropsch process. Using this line route, some of the gaseous wastes of the oil-processing plants and oil-commercial fields can be converted to valuable fuel oils blended with kerosene. Otherwise, the excess gas would be discharged to the atmosphere thus adding energy to global warming. The activities involve testing biofuels based on the jatropha (jatropha – an oleaginous plant that is doing well in arid areas) on the Boeing 747-400 aircraft. Finally, British Airways proposed to the suppliers to deliver fuel for testing on the RB211 engine at the covered test bench. In these tests' evaluation of engine operation, processing and emissions for each type of fuel are carried out. There is little likelihood that the wide-scale replacement of the kerosene in aviation will be favourable in the next decade [Parker R., Lathoud M., 2010]. Within the AAFEX program framework the CFM56-2C1 engine emissions of NO_x and CO were determined depending on the type of fuel used:

- Standard fuel JP-8 (or base);
- Fischer-Tropsch (FT) fuel, synthesized from natural gas (FT1), Shell corporation;
- Fischer-Tropsch fuel produced from Sasol coal (FT2);
- A mixture of FT1 and FT2 fuels with JP-8 in proportion 50:50.

In Figure 4.113 the values of $EINO_x$ emissions (standardized to the fuel caloricity value) are shown, depending on fuel consumption and environment temperature.

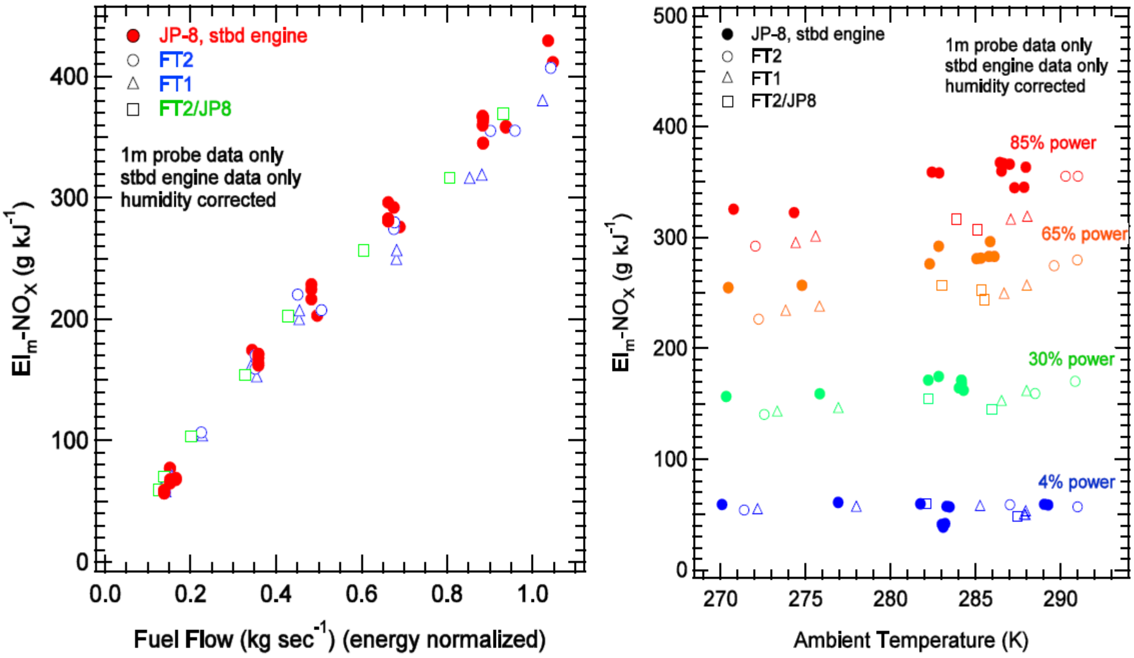


Figure 4.113: Results of investigations to the Alternative Aviation Fuel Experiment (AAFEX) program [*NASA/TM–2011-217059*]

The testing data suggest that the increase of the ambient temperature leads to an increase of the $EINO_x$ emissions for the power rating ≥ 30 %. The nature of $EINO_x$ emissions change with the ambient temperature increasing is the same for different types of fuels, and the $EINO_x$ emissions for the FT1 fuel were always lower than those for the JP-8 fuel.

On Figure 4.114, the EICO graphs are shown, depending on the fuel flow and the ambient temperature, for the ratings 4 %, 7 % and 30 % of nominal power.

According to the results of investigations [*NASA/TM–2011-217059*]:

– reduction of EICO by 10 % was achieved by using the FT1 fuel as regard to the JP-8 and FT2 fuels;

– the EICO emissions when using the FT1 fuel are lower than the emissions when using the JP-8 and FT2 fuels within the whole range of ambient temperatures investigated;

– the EICO ambient temperature dependence is foremost strong at the rating 4 % of nominal thrust and almost is absent (is within the confidence error range of the measuring equipment) for the ratings greater than 30 % of nominal thrust.

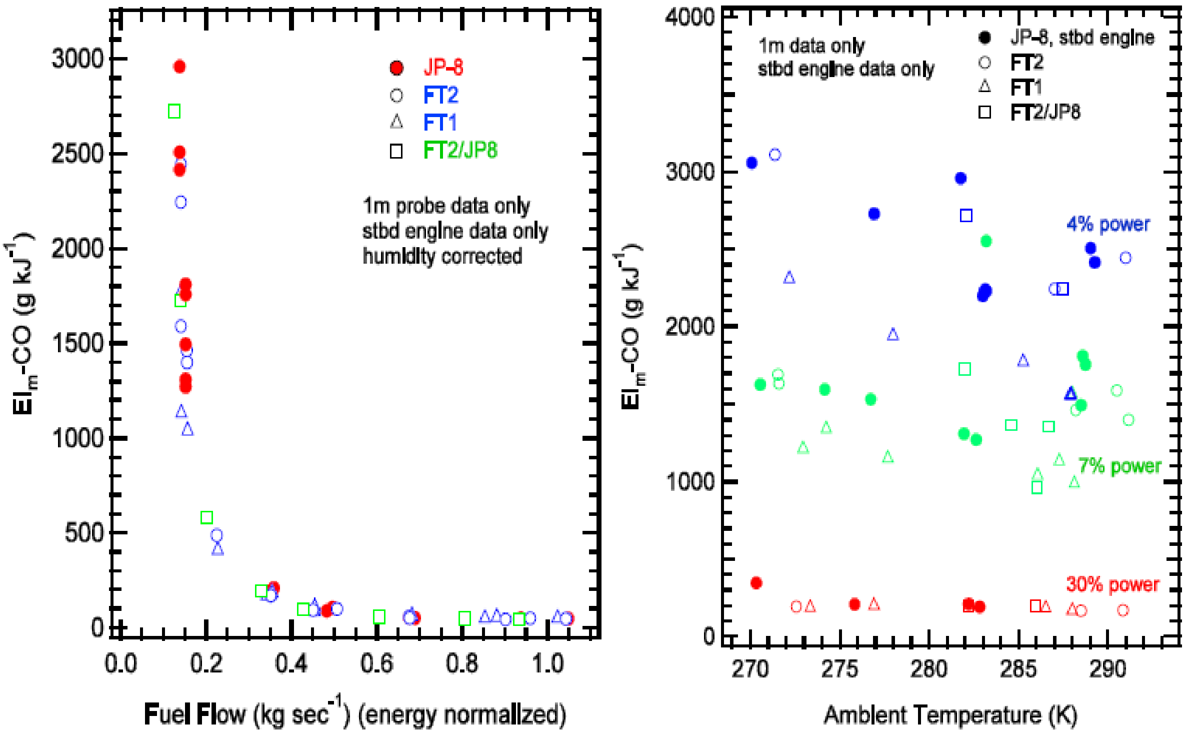


Figure 4.114: The results of investigations to the Alternative Aviation Fuel Experiment program (AAFEX) [*NASA/TM–2011-217059*]

On Figure 4.115 shown is the dependence of $EINO_x$ emissions on the thrust rating of engine operation when using the base and alternative fuels, as well as shown are the NO_x emissions measured during certification of the CFM56-2C1 engine that was carried out using the JET-A fuel.

The points “C” correspond to values obtained on the CFM56-2C engine during its ICAO certification [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/ 20110007202.pdf]. The reduction of NO_x by 5-10 %, achieved during carrying out investigations to the AAFEX program, is in line with two previous tests regarding the influence of the alternative FT fuels based on the natural gas on reduction of the NO_xи CO emissions: 1) Pratt & Whitney on the PW308 engine and 2) GE on the CFM56-7 engine.

For the PW308 engine operating at the rating of 85 % nominal thrust, the $EINO_x$ value was reduced approximately by 7 % for the FT fuel (Shell, natural gas) in reference to the JP-8. It is noted that the $EINO_x$ value at idle running is greater for the FT fuel tested on the PW308 engine, though the difference can be caused by the experimental errors. During testing the CFM56-7 engine the $EINO_x$ emissions were reduced by 11 % for the FT fuel (natural gas, Syntroleum) in reference to the Jet-A1.

The results of AAFEX tests indicate that one of the promising directions for decreasing the NO_x emissions is using the alternative fuels [*Alternative Aviation Fuel Experiment (AAFEX). Technical Report NASA/TM–2011-217059. Publication Date: Feb 01, 2011. - 408 p.*].

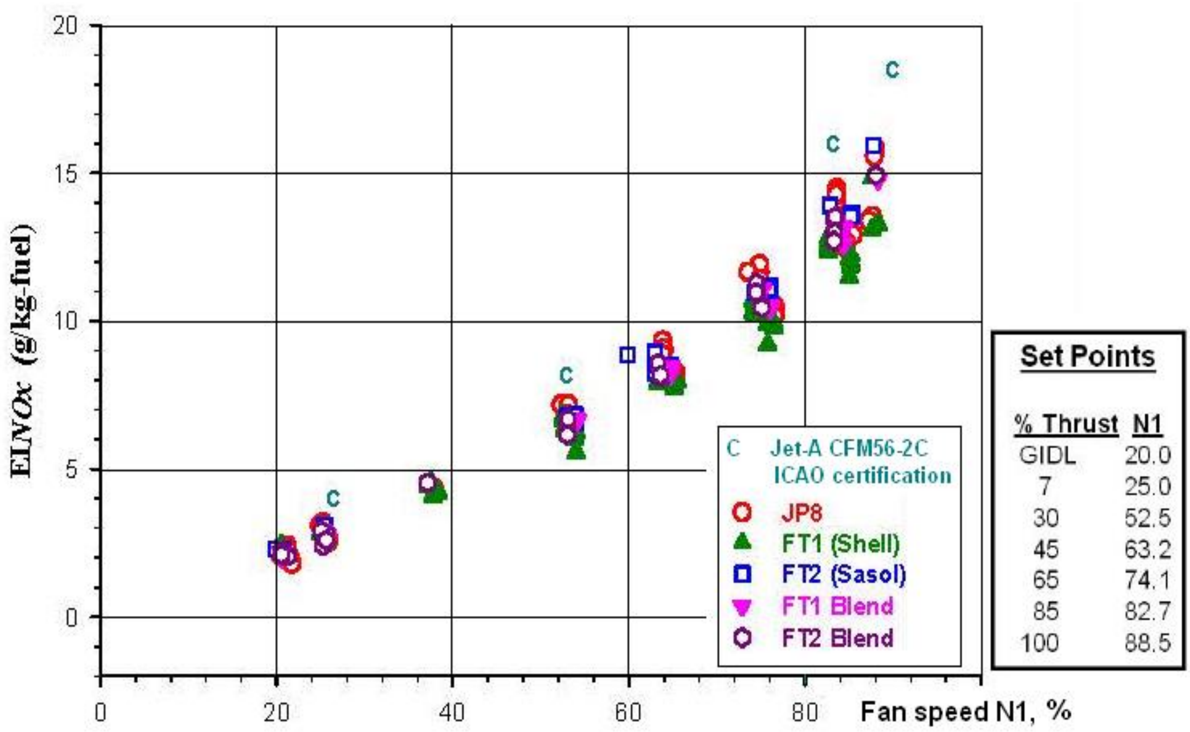


Figure 4.115: The results of strict policy investigations to the Alternative Aviation Fuel Experiment (AAFEX) program [*NASA/TM–2011-217059*]

Predictive appraisals of accomplishment of the ecological objectives up to the year of 2050 (Figure 4.116) and the biofuel emissions over the operational lifetime are analyzed in the work [SWAFEA: A European study of the feasibility and impact of the introduction of alternative fuels in aviation // Philippe Novelli. - IOS Press, 2011. – pp. 129-137. - DOI: 10.3233/978-1-61499-063-5-129]. As well, the price for biofuel is predicted (Figure 4.117).

At present, using biofuel in aviation is not of economic benefit because it is more expensive than the conventional aviation kerosene. As predicted by the experts, the oil prices can fall in already in the near future (Figure 4.117). This being the situation, one of the measures can be the legislative obligations to use in one or another proportion the purer, but simultaneously the more expensive alternative types of fuels. However, such measures will cause deterioration of the competitively of air transportation. According to Merrill Lynch' estimates, discontinuation of biofuel production will cause a rise in oil and benzine prices by 15 %. The incumbent China petroleum refining company Sinopec became a pioneer in creating this type of fuel from palm oil and recycled vegetable oil for food preparation, at the Zhenhai Refining and Chemical Company factory. The first evaluation flight of the China Eastern Airlines' Airbus A320 airliner with this type of fuel was carried out in April 2013.

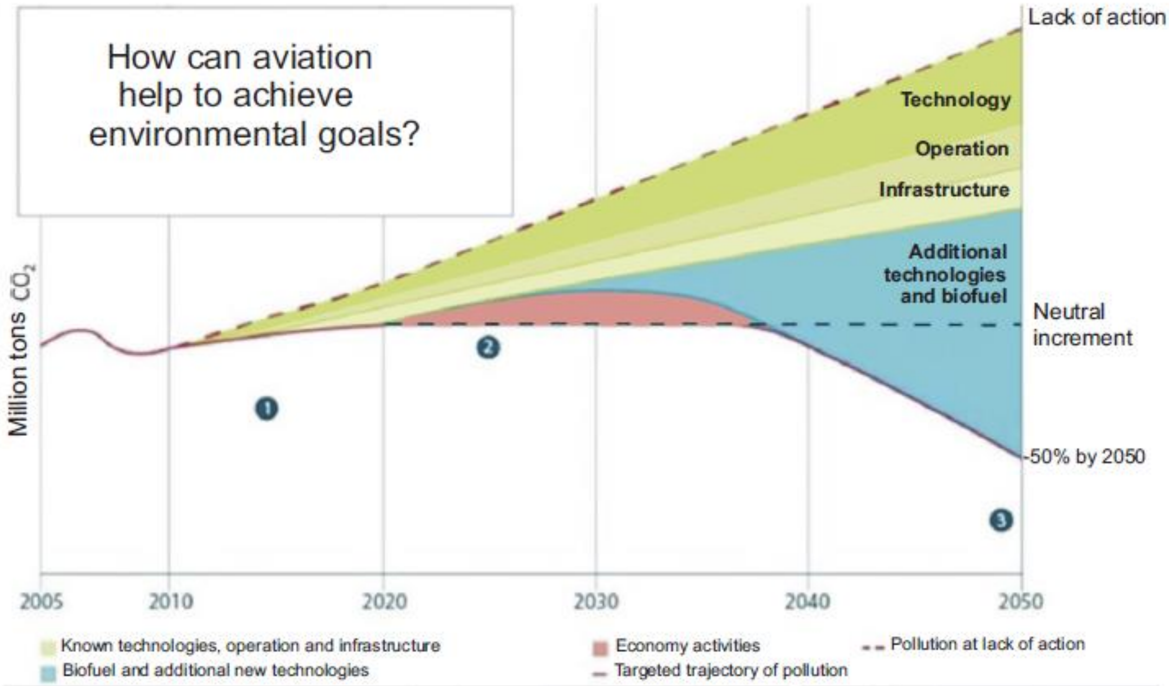


Figure 4.116: Predictive appraisal of accomplishing the ecological objectives 2050

Currently, the main problem in the way of biofuel commercial application is the biofuel price. The biofuel produced in accordance with the resource-recovery technologies throughout its life cycle reduces the carbon dioxide by 50-80% in comparison with the oil fuel, and therefore it will have a dominant role in supporting the aviation growth with simultaneous improvement of the ecological indices (Figure 4.118). According to Boeing's annual commercial aviation market forecast, for meeting the booming demand on internal and international passenger transportation at 2033 it will be necessary for China more than 6000 new airplanes. It is necessary also to be taken into account that the ecology movement and the introduction of EU ETS exert influence on the commercial aviation in terms of introducing, in the very near future, an additional ecological tax for the airlines.

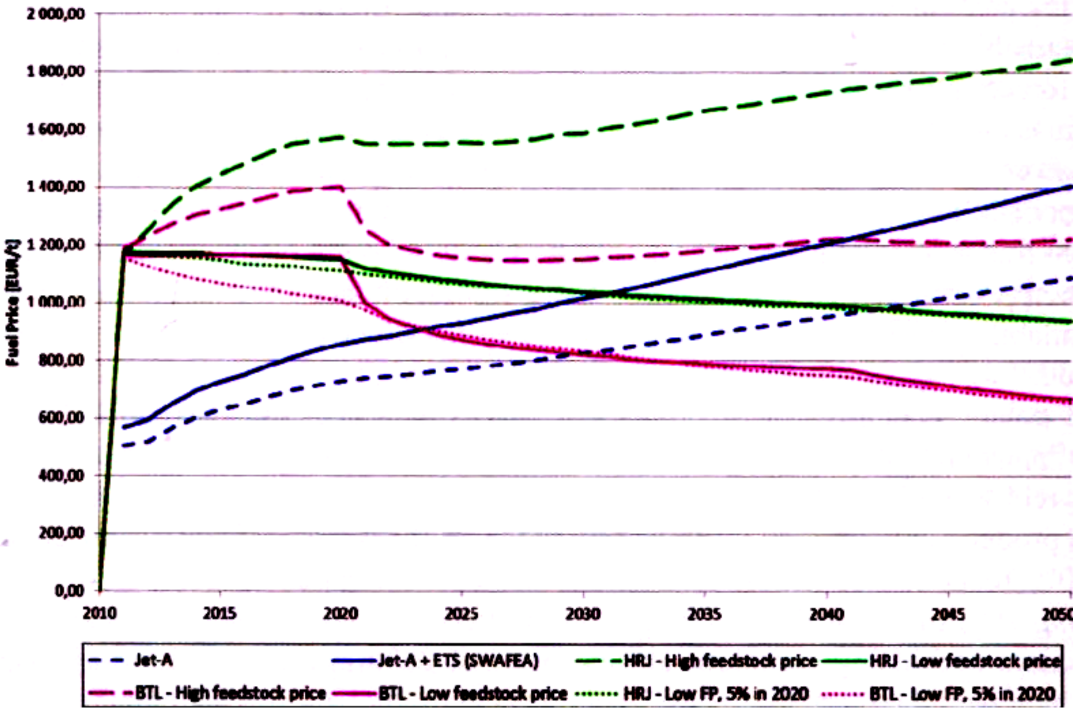


Figure 4.117: Biofuelprice forecast

Two main scenarios based on a possible change of the oil price are taken in consideration. In the first instance the price decreases, in the second, increases.

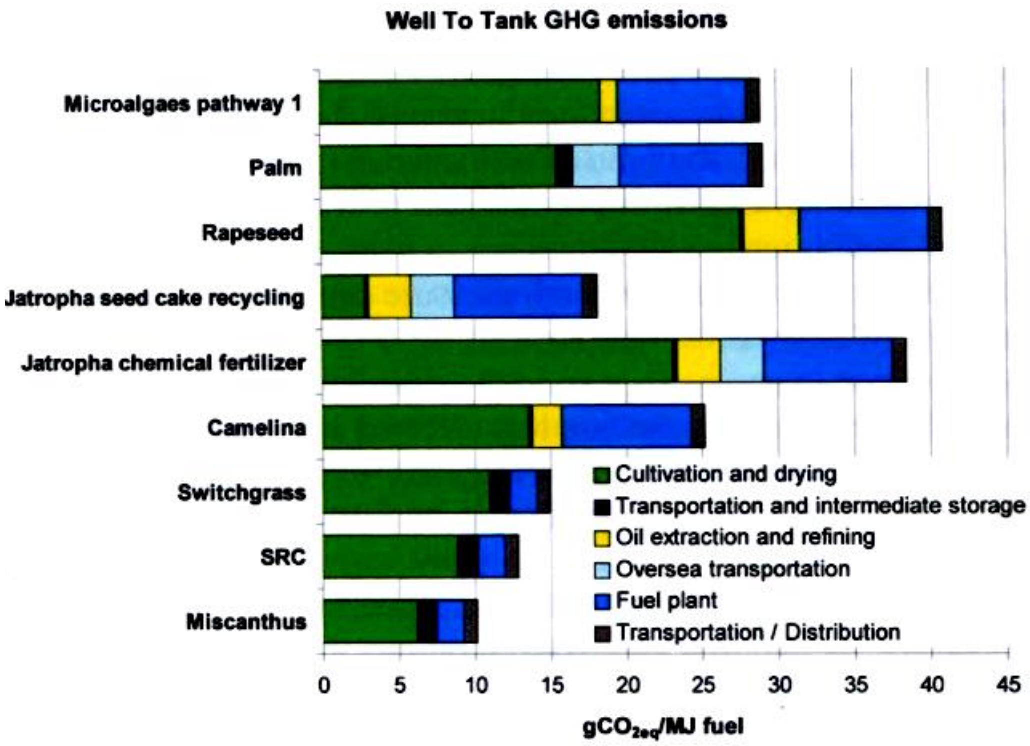


Figure 4.118: Biofuel emissions over the life cycle

The first scenario supposes an extremely pessimistic forecast for using the biofuel, dismantling of investigations and reduction of areas used for growing appropriate agricultures. According to this scenario, if the fall in prices lasts long duration, the biofuel production can be ceased at all, and nothing will be said here about its any use. As prerequisites for such a scenario serve may the following: development of light tight oil production technologies, entry into oil market of new producers from Africa, America and Asia, general curtailment on oil demand in other industry sectors, reduction of global economics, and other factors.

The second scenario is favourable for mastering the biofuel and widening its usage. However, there will be not an immediate growth of its consumption, since this requires significant changes in the technological infrastructure of commercial aviation, which can take place not immediately. As prerequisites for such a scenario serve may the following: the growth of global economics and international trade, reduction of oil production, cost reduction of biofuel production and a number of other reasons.

Possible alternative aviation fuels.

Biofuels

In the initial 2011 Biofuel Flightpath document, only three candidates were considered, but by now several alternative biofuels are under scrutiny or already approved[10].

- Synthetic Fischer-Tropsch (FT) based kerosene produced through biomass gasification

Fischer-Tropsch synthesis entails a process which produces a gaseous mixture of hydrogen and carbon monoxide called syn-gas, over the surface of a catalyst 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.

- Hydrogenated Esters and Fatty Acids (HEFA) and Hydrogenated

HEFA derived synthetic paraffinic kerosene is based on triglycerides and fatty acids which can originate from plant oils, animal fats, algae and microbial oil. Hydrogen demand for hydroprocessing of different feedstock qualities varies, resulting in conversion cost advantages

[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

for certain raw materials like palm oil and animal fats. HEFA production is already proven on a full commercial scale. Neste Oil operates two 190,000 t/a HEFA plants in Finland and one 800,000 t/a plant each in Singapore and Rotterdam. UOP and its customers have announced several HEFA projects worldwide. In Europe, both ENI and Galp Energia have plans for HEFA plants at 330,000t/a each, but these facilities are designed for diesel replacement in road transport and as such cannot be used for aviation unless some process modifications are carried out on the existing facilities.

- Pyrolysis Oils (HPO) produced from lignocellulosic biomass.

HPO is still at a research phase. It entangles developing fast pyrolysis processes. A few of them (e.g. Ensyn/Envergent Technologies (a joint venture between UOP and Ensyn Corp from Canada) and BTG in the Netherlands) are implementing the pyrolysis process on a commercial scale to produce crude pyrolysis oil. Pyrolysis oil, unlike vegetable oils (VO), contains a few hundred different chemical species. For application in the transport sector, the crude oil needs further upgrading to produce HPO. One or more hydrogenation steps are required to achieve the desired product quality. The scale of operation for producing the pyrolysis oil can be quite different from the upgrading activities. The latter one might be combined with current refinery operations. Envergent/UOP, for example, is conducting a demonstration project for Pyrolysis and the Upgrading technology to transport fuels at the Tesoro refinery in Hawaii. Contrary to FT and HEFA fuels HPO will still contain a certain number of aromatic compounds which are currently needed in jet fuel to avoid engine sealing problems. Therefore, HPO may complement HEFA and FT.

- Alcohol to Jet (ATJ)

The alcohol to jet (ATJ) is characterised by the production of alcohols as an intermediate product derived from biomass as shown in Figure 4.119:

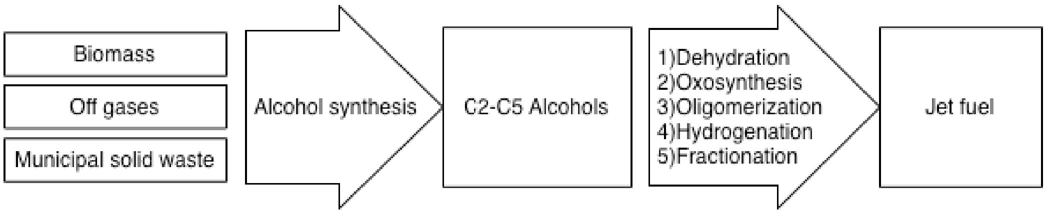


Figure 4.119: Possible pathways to obtain ATJ biofuel. Source "2 million tons per year: A performing biofuels supply chain for EU aviation - August 2013 Update http://ec.europa.eu/energy/technology/events/2011_05_18_biofuels_in_aviation_en.htm)

The overall process consists of alcohol synthesis from the raw materials followed by chemical synthesis into jet fuel. An advantage of ATJ technology is that it can be fully integrated with a wide variety of different front-end technologies for the production of alcohol intermediates. ATJ is currently still at pilot plant scale. Major players are Swedish Biofuels AB in Europe and Gevo in the United States. The technology called Direct Sugar to HydroCarbons, DSHC, developed by Amyris and Total, produces pure iso-paraffinic molecules by fermentation of any type of sugar, followed by mild hydrogenation. The first industrial molecule, a C15 hydrocarbon called farnesane, can be safely incorporated in fossil jet-fuel at 10% and ASTM certification is presently underway.

Advantages and limitations

Advantages

The most important motivations for biofuel usage concern the mitigation of climate change, the reduction of fossil fuel dependence, the conservation of biodiversity and water, as well as the development of agriculture. For example, F-T jet fuel has been shown to reduce particulate emissions without affecting engine performance. F-T fuel is characterized by excellent thermal stability at elevated temperatures and very good properties at low temperatures.

Limitations

Potential negative impacts of biofuel usage can be associated with the massive production of a few vegetal species with detrimental effects on global biodiversity and the triggering of market reactions to increased production of feedstock.

Current status and future prospects

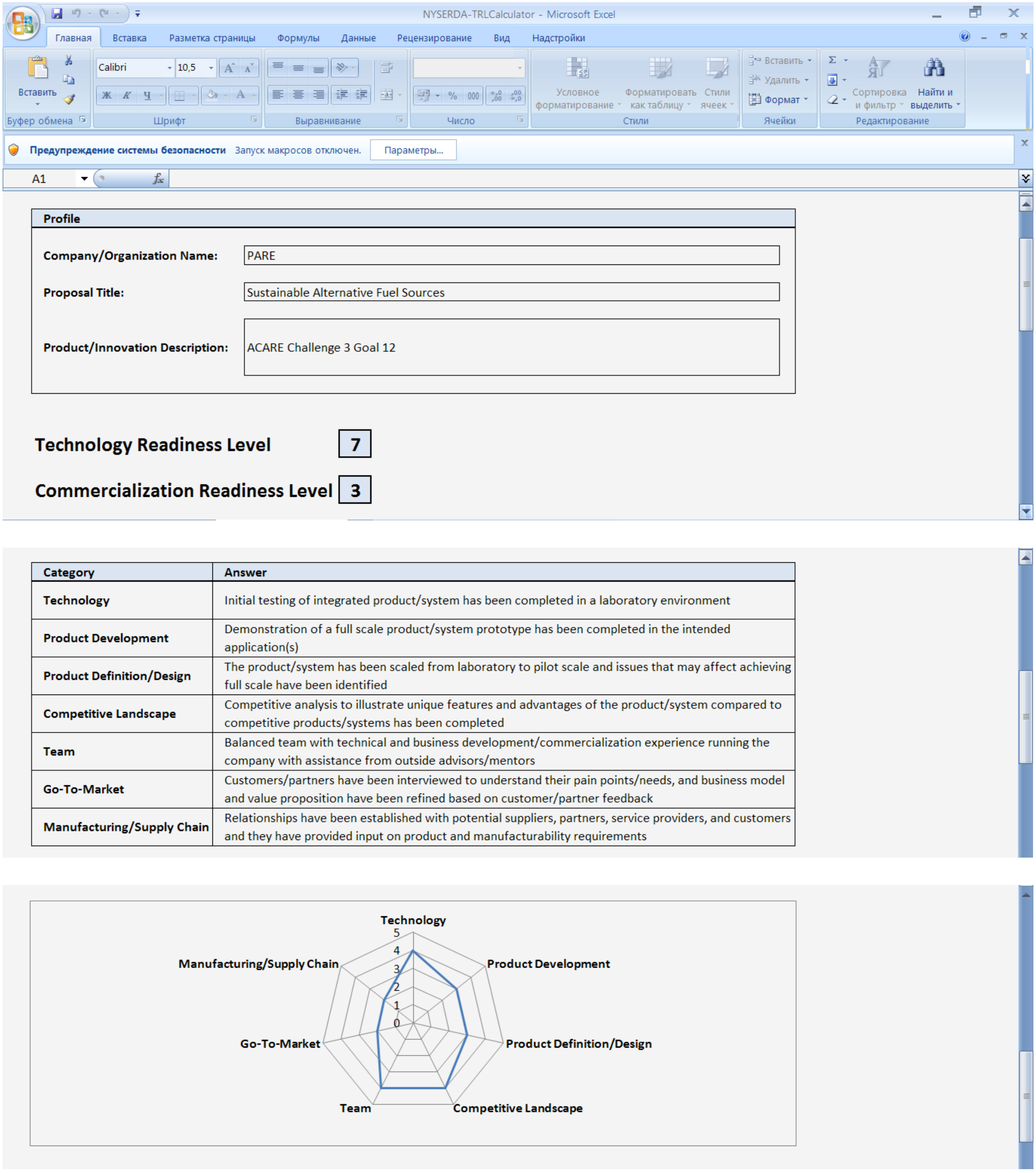
The use of alternative biofuels has been explored under 7thFP European project "ITAKA"[12] (2012-2016). The main milestone achieved concerns the use of bio-jet blend mixed in the conventional airport fuel systems (tanks, pipelines, hydrants) during conventional operation of the airport. This logistics 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 bio-jet fuel blend (below 3%), which corresponds to about 60,000 flights and about 6 million of passengers. The bio-jet fuel was the camelina oil 100% made in the EU. It was produced in Spain (accumulated in three seasons, more than 1000 t), and refined to bio-jet fuel in Finland. Camelina plantations have been cultivated in a wide range of climatic and soil conditions. As a consequence, camelina yield has varied from 500 to 2,500 kg per hectare, depending on the cultivation and weather/soil conditions. Barley data has been used as an indicator of land quality. So, a farmer harvesting 3,000 kg/ha of

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

barley in a given year should expect a camelina harvest of 1,500 kg/ha (50%). It has been demonstrated that sustainable camelina oil can be produced in Europe, in large amounts, with low risk of ILUC (Indirect Land Use Change), generating additional social and economic benefits for the farmers. The GHG (greenhouse gases) savings in a scaled-up production can achieve a 66% reduction. Besides, the savings can go over 70% if a fertilization strategy is put in place, using i.e. ammonium sulphate (NH_4) instead nitrate (NO_3) for fertilization.

The use of the biofuel has been tested in two series of flights. The first series of 18 long haul flights from Amsterdam to Aruba, on an Airbus A330-200 (carrying around 4,500 passengers informed about the project) was performed using bio-jet fuel blend in one engine to compare the performance of the two engines. No significant performance differences were noted, but that the water accumulated in the tanks during flights can be lowered using the synthetic fuel, reducing the maintenance frequency and costs. The second series of 80 short-haul flights, from Oslo to Amsterdam, on an Embraer E190, carrying about 8,000 passengers, using the camelina bio-jet blend in both engines, confirmed the no detrimental effects on operation with similar or slightly better fuel consumption and, no variation in fuel gauging systems. The flight series was complemented with a series of lab-based emission measurements using a testbed Auxiliary Power Unit (APU). APU emissions tests were completed for the two ITAKA fuel batches and baselined against a standard fossil Jet fuel: performance parameters were as expected quite similar, fuel consumption decrease up to 1% (saving fuel and CO_2 emissions), and the emitted particulate matter (PM) was decreased up to a 50% for a 50:50 fuel blend. PM emissions are a major air quality concern that is linked with a significant number of premature deaths across Europe. High paraffinic fuels such as HEFA bio-jet could significantly help to reduce the impact of this pollutant in the vicinity of airports. The information obtained has been supplied to the International Civil Aviation Organization for the development of future standards for aircraft engines.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 12** "Sustainable Alternative Fuel Sources" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.120 grounding on the results of the 1st year PARE report (PARE D1.1, 2018).



Category	Answer
Technology	Initial testing of integrated product/system has been completed in a laboratory environment
Product Development	Demonstration of a full scale product/system prototype has been completed in the intended application(s)
Product Definition/Design	The product/system has been scaled from laboratory to pilot scale and issues that may affect achieving full scale have been identified
Competitive Landscape	Competitive analysis to illustrate unique features and advantages of the product/system compared to competitive products/systems has been completed
Team	Balanced team with technical and business development/commercialization experience running the company with assistance from outside advisors/mentors
Go-To-Market	Customers/partners have been interviewed to understand their pain points/needs, and business model and value proposition have been refined based on customer/partner feedback
Manufacturing/Supply Chain	Relationships have been established with potential suppliers, partners, service providers, and customers and they have provided input on product and manufacturability requirements

Figure 4.120: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 12** “Sustainable Alternative Fuel Sources”

4.5 Atmospheric Research, Weather and the Environment

**** Flightpath 2050 goal 13: "Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritized environmental protection plan and the establishment of global environmental standards".***

Atmospheric hazards have been a safety concern throughout the history of aviation and are addressed in goal 15 (section 4.2). A better modelling and understanding of atmospheric phenomena can reduce disturbances of air traffic management (goal 5 and section 2.5) and allow an increase of runway capacity at airports (goal 1 and section 2.1). As major users of the airspace aviation can contribute to the monitoring of the atmosphere and to the establishment and implementation of global environmental standards. The monitoring of the atmosphere is performed by a vast array of earth and satellite sensors, plus specialized weather aircraft like those used by NOAA (National Oceanographic and Atmospheric Administration in the US) to fly through tropical storms and collect in-situ atmospheric data. The data transmission capabilities of airliners in modern ATM systems could be used not only for traffic proposes but also to collect atmospheric data in support of environmental standards and policies. It is in the interest of airlines to preserve their flight environment and if appropriate some of the millions of flight around the world could be a source of in-situ measurement and monitoring. More details on the contribution of aviation to the undertakings of atmospheric and weather effects are given in the Key Topic T4.5.

KEY TOPIC T4.5 – WEATHER EFFECT ON AIRCRAFT OPERATIONS

Scope of the goal

Atmospheric research: weather and environment		
<u>Goal 13:</u>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 4.22: ACARE Flightpath 2050 Goal 13

Benchmarks for Goal 13

There are two ways of assessing the atmosphere impact:

On the one hand, evaluating the impact of the atmosphere on aviation which is analysed in goal 15. In this goal, weather and other hazards from the environment are precisely evaluated and risks properly mitigated.

On the other hand, it is necessary to evaluate the aviation impact on the atmosphere. This impact can be negative such as the CO_2 and NOx emissions and the noise disturbances which are analysed in detail in goal 9.

Finally, within the aviation impact on the atmosphere, it is important to assess how aviation can contribute to the atmosphere knowledge. This is the objective to be evaluated in the goal 13: "Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritized environmental protection plan and the establishment of global environmental standards".

In quantitative terms, the objective to be achieved could be that the 100% of the data that the aircraft can obtain and process from the atmosphere could be shared between other aircraft and ground infrastructure that would allow obtaining a real-time atmospheric model capable of predicting weather hazards as well as to evaluate the possible geographic location of these threats.

In order to achieve this objective, it would be necessary for a series of measures such as those proposed in the following points:

- Aircraft equipped with systems capable of processing a great amount of data
- Communications network
- Real-time broadcast
- Prediction models

Aircraft equipped with systems capable of processing great amount of data

Aircraft would need to have onboard systems capable of processing significant amounts of information from the environment (not only atmospheric which is the main purpose of this goal but also another kind of information which can be useful for the rest of goals).

Some initiatives which are currently in development are new modern aircraft engines such as the Pratt & Whitney's Geared Turbo Fan (GTF) engine which is fitted with 5,000 sensors that generate up to 10 GB of data per second, which could result in 800 TB per day and per engine. Taking into account the goal of 25 million flights, it would be necessary that aircraft generate on average 6000 million TB of data to comply with the goals to be achieved. This is called Aviation 4.0 which is part of the upcoming Industry 4.0 revolution. Industry 4.0 refers to the current trend of higher levels of automation, digitalization and data exchange in manufacturing technologies. It includes cyber-physical systems, the Internet of Things and cloud computing among other technological assets.

Within this Industry 4.0, the concept of aviation 4.0 is introduced, which establish the evolution of commercial aircraft. With this type of digital and smart 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 can sense their environment, self-diagnose their condition and adapt in such a way so as to make the design more useful and efficient thanks to their information technology, measurement science, sensors, actuators, signal processing, cybernetics, artificial intelligence, etc.

In addition, this type of aircraft offers significant improvements in aircraft total weight and manufacturing cost. It also helps to improve the aircraft's life cycle, reduce its maintenance and decrease generated noise. One example of these aircraft is the A350, the new and latest member of the Airbus family.

Communications network

An aircraft should have an advanced communication system, capable of transmitting data through multiple datalinks, directly to the ground, to other aircraft and via satellite, digitally and at high speed, providing communication services for all aircraft needs, each with its own required quality of service. In this way, all the detailed information, such as the weather situation, obtained from the on-board equipment and the sensors can be shared between the ground infrastructures and the aircraft in a quickly and reliably. However, this system should be economic so that installing it on as many aircraft as possible will be profitable. In addition, this communication system should be safe, robust and resilient to the possible cyberattacks since the system will need larger bandwidth due to the great amount of data exchanging.

Real-time broadcast

The data obtained from the aircraft sensors is broadcasted to all the stakeholders, such as other aircraft and the ground infrastructure in real-time. In this way, the whole system will be aware of the possible weather threats and their possible location. In addition, all this information could be used to develop prediction models that would allow predicting weather hazards in advance.

Prediction models

Thanks to all the data obtained from the equipped systems and their broadcasted to other stakeholders, predictions models could be obtained in order to foresee the possible weather hazards.

One example could be to identify and locate the areas with the presence of ice crystals thanks to the sensors equipped in the aircraft. The presence of High-altitude ice crystals causes engine damage and engine power loss. There are some initiatives that research how to identify the formation of these crystals through the sensor TAT (Total Air Temperature). This is because Total Air Temperature (TAT) anomaly has occurred in many cases near the time of the engine power loss events. When this sensor reports zero degrees it is evidence of ice crystals present in the atmosphere. This anomaly is due to ice crystals building up in the area where the thermocouple resides, where they are partly melted by the heater, causing the zero degrees reading. Therefore, TAT anomalies monitoring might alert of areas in which it is probably the presence of High-altitude ice crystals and this information could be shared between other aircraft and the ground infrastructure in real-time. Figure 4.121 illustrates the benchmarks discussed for goal 13.

Reference State in 2010

Environmental issues and climate risks

Aviation is one of the most climate/weather sensitive industries. It is affected by changes to visibility, storminess, temperature, icing events, flooding events, and the operational effects of these. Therefore, one of the most important activities is to assess the atmosphere and the environment state in order to predict future climate issues and develop mitigation strategies.

This will help to reduce possible disturbances in the airspace and may allow for an increase in airports capacity.

Environmental policy in the European Union developed substantial improvements to the state of the environment. However, there were still major environmental challenges which have significant consequences for Europe, and they continue to be investigated nowadays. Taking this into account, the European environment policy priority areas are the following ones:

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

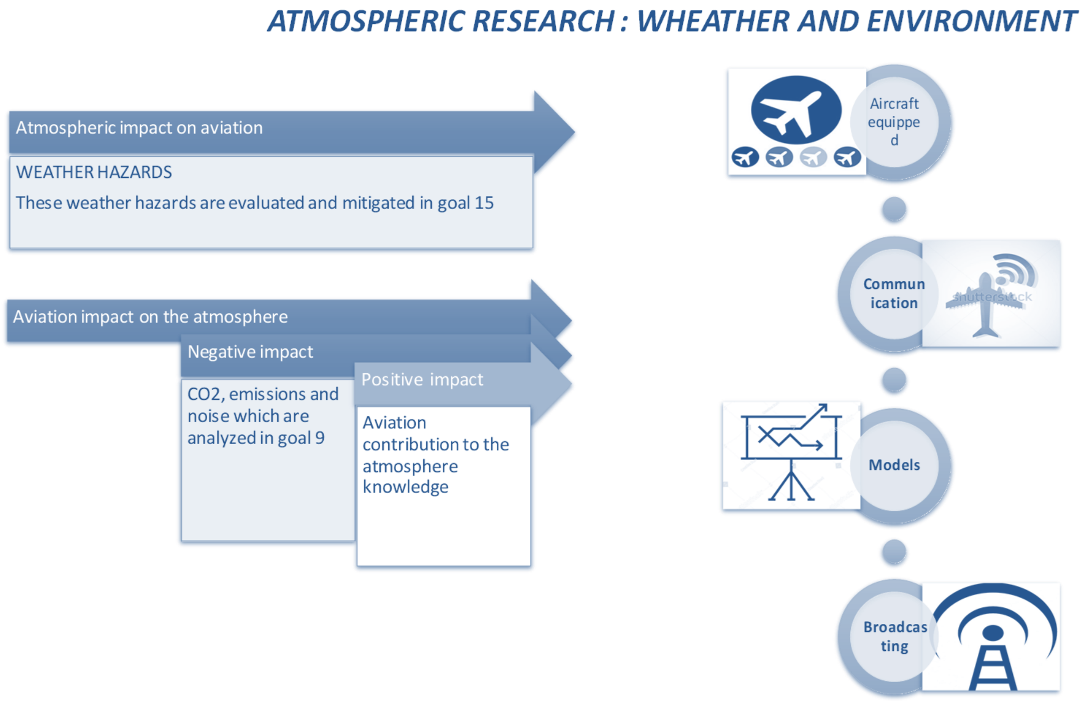


Figure 4.121: Benchmarks for goal 13

➢ Climate change

Climate change has become one of the most environmental concerns since it has a wide range of consequences for biological and socio-economic systems. Aviation is a small but important contributor to climate change and, for that reason, in recent years considerable effort has been carried out to mitigate aviation's impact on the climate and to increase Europe's resilience. Some climate change effects are in the following Table 4.23:

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 4.23: 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 4.24):

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 4.24: Endangered species and ecosystem

- Natural resources and waste

Environmental regulation has increased resource efficiency through a relative decoupling of resource use, and waste generation (Table 4.25):

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 4.25: Waste generation and management

➢ Environmental and health

Water and air pollution have declined but not enough to achieve good ecological quality in all water bodies or to ensure the good air quality in all urban areas (Table 4.26):

Water quality	**The quality of water supply in coastal and island regions is at risk from rising sea level and changes in precipitation. Rising sea level and the occurrence of drought can increase the salinity of both surface water and ground water through saltwater intrusion.**
Air quality	the quality of air overpopulated areas is of continuing concern as the degradation of air quality has a major impact on human health, agricultural productivity and natural ecosystems

Table 4.26: Water and Air quality

All these environmental issues result in climate risks and impacts for aviation which are shown in the following Table 4.27:

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

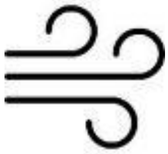
Wind changes 	convective weather: disruption to operations and route extensions jet stream: potential increase in en-route turbulence local wind patterns: potential disruption to operations and changes to distribution of noise impact
Extreme events 	disruption to operations, route extensions disruption to ground transport access disruption to supply of utilities

Table 4.27: Climate risks and their impact

Monitoring the atmosphere

Taking into account the main environmental issues and their effects on aviation, it is essential to develop a series of methods that allow to assess the atmosphere state and to measure its composition with to face these issues and to develop mitigation strategies.

There are several methods to monitor the atmosphere to state its composition in order to face the global issues mentioned before:

- Routine ground-based measurements
- Systematic aircraft measurements;
- Satellite measurements

➢ <u>Ground-based instrumentation</u>

Thanks to new technologies and a variety of sophisticated measurement techniques, it is possible to measure accurately the atmosphere composition. The globally distributed ground stations provide high-quality observations for:

- detecting long-term trends in atmospheric concentrations;
- monitoring air quality on a regional to global scale;
- evaluating and developing regional to global scale models that include atmospheric chemicals (e.g. local and regional weather and air quality forecast models, long-range transport models and climate models);
- and calibration and validation of satellite observations

Several initiatives monitor and observe the atmosphere such as the Global Atmosphere Watch programme of WMO, which coordinates global ground-based networks measuring greenhouse gases, ozone, UV radiation, aerosols, atmospheric pressure, wind speed and direction, air temperature and relative humidity.

- Airborne instrumentation

Thanks to the on-board systems, aviation offers a cost-effective and efficient way of collecting information related to atmospheric conditions and state. Continuous, real-time information captured and communicated by aircraft can be used to update weather observations in a reliably way and to increase weather prediction capabilities. There are several programs whose objective is to evaluate the atmosphere state by using data collected from the aircraft system:

IAGOS (In-service Aircraft for a Global Observing System): it is a European research infrastructure which aims at constructing a global observation system for atmospheric composition by deploying autonomous instruments aboard a fleet of passenger aircraft. It is one component of the European Research Infrastructure for gathering long-term, routine in-situ observational data on the state of the atmosphere. By deploying a set of autonomous instruments aboard passenger aircraft of internationally operating airlines, IAGOS collects crucial atmospheric data at a global scale. The first IAGOS aircraft went into service in 2011, namely aircraft equipped with fully automated instruments for the measurement of several parameters such as ozone, carbon monoxide, and humidity (ICH) and cloud particles (BCP).

MOZAIC (Measurement of Ozone and Water Vapour on Airbus In-service Aircraft): it is a European program that uses automatic instruments for probing atmospheric state parameters and chemical composition, such as water vapour, ozone and carbon monoxide. These instruments have been installed on several commercial aircraft in 1994 and have, since then, provided regular data for the upper troposphere/lower stratosphere with more than 2000 flights and 4000 tropospheric profiles per year.

The SpectraSensors Water Vapour Sensor System (WVSS-II) provides laser fast and accurate measurement of water vapour in the upper atmosphere, which is an essential parameter for accurate weather modelling. The water vapour detection helps to improve the forecasting of weather and climate change. A fleet of aircraft equipped with the Water Vapour Sensor System (WVSS-II) can provide thousands of times the number of vertical profiles accurately, automatically, and at a fraction of the operational cost.

EUFAR: EUFAR was born out of the necessity to create a central network for the airborne research community in Europe with the principal aim of supporting scientists, by granting them access to research aircraft and instruments otherwise not accessible in their home countries. In this way, scientists all over Europe can have an equal chance to carry out various atmospheric and in situ measurements onboard research aircraft.

As can be seen, aircraft measurements are one of the most efficient tools for obtaining representative information of the troposphere and stratosphere at high resolution and with uniform quality.

In addition, these types of measures are really important since global climate change represents one of the most serious environmental issues today. Reliable predictions of the future climate using climate models are central and fundamental requirements for determining future mitigation strategies. The use of commercial aircraft allows the collection of highly relevant observations on a scale and in numbers impossible to achieve using research aircraft, and where other measurement methods (e.g., satellites) have technical limitations.

Land and sea bared sensors and data collected by aircraft are complemented by satellites.

- Satellite instrumentation

Compared to measurements made by ground-based sensors (land-based and buoys) and by airborne instrumentation (aircraft and balloons), the advantage of space-borne sensors is their global three-dimensional coverage and regular repeat cycle.

Meteorological satellites have been successfully used for tropospheric measurements of clouds and other parameters required for weather prediction. Geostationary satellites can be used to measure wind velocity by tracking clouds and water vapour. Satellite sensors, communications and data assimilation techniques are evolving steadily so that better use is being made of the vast amount of satellite data. Improvements in numerical modelling, in particular, have made it possible to develop increasingly sophisticated methods of deriving the temperature and humidity information directly from the satellite radiances.

Research satellites, such as ENVISAT and AURA, contribute strongly to monitor atmosphere composition.

ENVISAT: Envisat was launched as an Earth observation satellite. Its objective was to service the continuity of European Remote-Sensing Satellite missions, providing additional observational parameters to improve environmental studies. Currently, scientific disciplines use the data acquired from the different sensors on the satellite, to study such things as atmospheric chemistry, ozone depletion, biological oceanography, ocean temperature and colour, wind waves, hydrology (humidity, floods), agriculture and arboriculture, natural hazards, digital elevation modelling (using interferometry), monitoring of maritime traffic, atmospheric dispersion modelling (pollution), cartography and study of snow and ice. The contact with the satellite was lost in 2012.

AURA. Aura is a multi-national NASA scientific research satellite in orbit around the Earth, studying the Earth's ozone layer, air quality and climate. The scientific findings of these studies address key NASA research objectives related to stratospheric composition, air quality, and climate change.

Aura's instruments measure trace gases in the atmosphere by detecting their unique spectral signatures. MLS (Microwave Limb Sounder) observes the faint microwave emissions from rotating and vibrating molecules. HIRDLS (High-Resolution Dynamics Limb Sounder) and TES (Tropospheric Emission Spectrometer) observe the infrared thermal emissions also due to molecular vibrations and rotations. OMI (Ozone Monitoring Instrument) detects the molecular absorption of backscattered sunlight in the visible and ultraviolet wavelengths.

Progress up-to-now

A brief description of current European projects is shown below. The objective of these projects is to assess the atmosphere state through ground and satellite infrastructure:

Copernicus: previously known as the Global Monitoring for Environment and Security (GMES) programme, Copernicus is a European Union programme aimed at developing European information services based on satellite Earth Observation and in situ (non-space) data. The provision of Copernicus services is based on the processing of environmental data collected from Earth observation satellites and in situ sensors. Copernicus services are based on information from a dedicated constellation of satellites, known as “Sentinels”, as well as tens of third-party satellites known as “contributing space missions”, complemented by “in situ” (meaning local or on-site) measurement data. In situ data are an essential and integrated part of Copernicus used to provide robust integrated information and to calibrate and validate the data from satellites (e.g. ground-based weather stations, ocean buoys and air quality monitoring networks).

EUMESAT: is the European operational satellite agency for monitoring weather, climate and the environment. EUMETSAT operates a fleet of satellites in geostationary and polar orbit, which provide a wide array of Earth observation data for weather, climate and environmental monitoring. The ground segment constitutes the ground-based infrastructure necessary to support the operation of the satellites, including the control of the spacecraft in orbit, and the acquisition, reception, processing and delivery of their data.

The Global Atmosphere Watch (GAW): it is a programme of WMO which provides reliable scientific data and information on the chemical composition of the atmosphere, its natural and anthropogenic change, and helps to improve the understanding of interactions between the atmosphere, the oceans and the biosphere. Monitoring has focused on greenhouse gases and aerosols for possible climate change, ozone and ultraviolet radiation for both climate and biological concerns, and certain reactive gases and the chemistry of precipitation for a multitude of roles in pollution chemistry.

Finally, it is important to note that, in this objective, it is very difficult to differentiate between the 2010 state of the art and the 2017 state of the art due to several reasons:

On the one hand, the European projects mentioned before, which have as objective monitoring the atmosphere, has been in development for several years. On the other hand, the main environmental issues described before (such as climate change), that concern nowadays and which arose years ago, are still under study. In addition, it is important to highlight that the timeframe of these aspects extends into a broader period. For these reasons, it is difficult to evaluate accurately the progress made from 2010 to 2017.

Existing technologies, breakthrough technologies and evolutionary progress up-to-2050

Atmospheric composition matters to several areas such as climate, weather forecasting, human health, terrestrial and aquatic ecosystems, aeronautical operations, etc. Due to its importance, it is necessary to develop new and enhanced methods to evaluate its composition in order to better understand the future environmental issues and carry out mitigation plans. The principal missions and goals for long-term horizon are the following ones:

- Ensuring that the climate continues to be monitoring by applying new techniques that provide better predictions.
- Improving global, regional and local long-term climate forecasts
- Observing atmospheric additional parameters
- Many environmental issues that should be considered in the future, which are explained in the section.

Environmental issues and climate risks

As it happened nowadays, climate change will be considered as the main environmental issue of risk. Although in recent years the aviation sector has initiated several measures and actions to mitigate the climate change effects, it is clear that its effects will not be fully neutralized and, as a consequence, some degree of climate change will be inevitable. In addition, other environmental hazards will emerge and, therefore, new mitigations strategies will be necessary. Moreover, taking this into account the aviation sector will need to build climate resilience and to adapt to the emerging threats.

In the following Table 4.28, it is shown the main climate risks, their effects and their impact on European aviation. It covered a time horizon up until 2050, a period where initial impacts may begin to be experienced by the industry.

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 4.28: 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 the delay.

Environmental issues forecasts by region

In the following images, it can be seen the potential environmental issues and their main impacts on aviation in Europe. It is expected that these possible effects vary greatly with the region as shown in Figures 4.122 and 4.123:

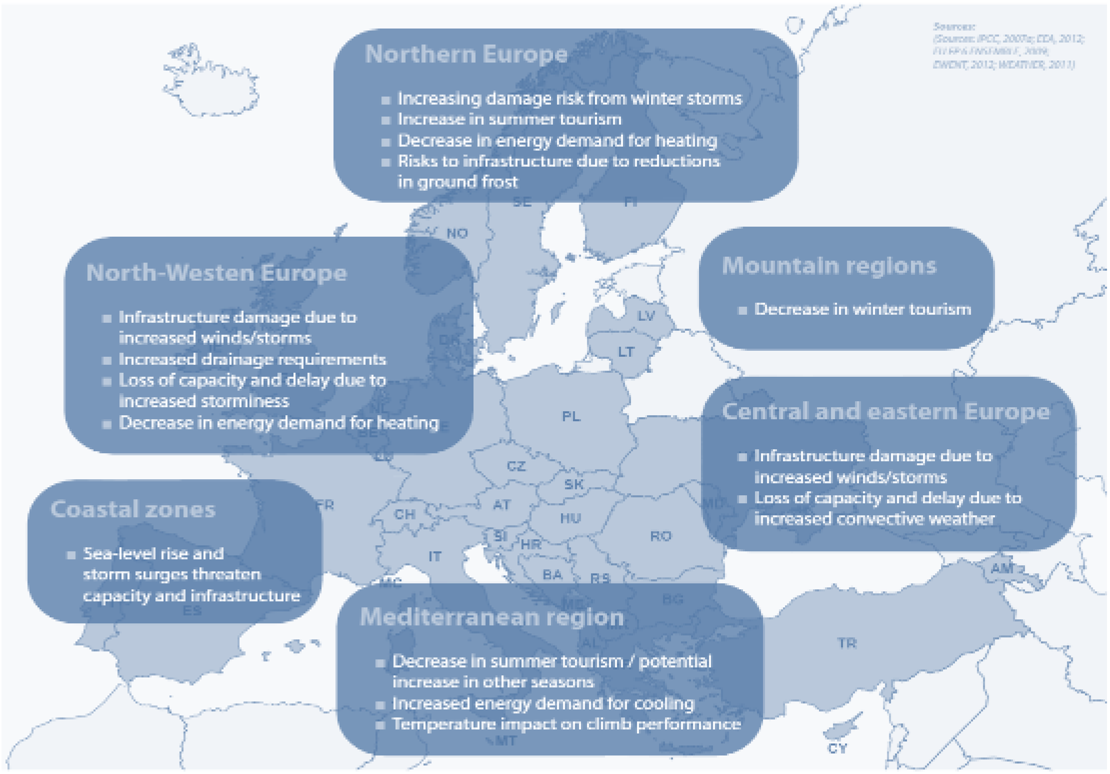


Figure 4.122: Environmental issues effects by region

Duration and timing of environmental impacts

In this section, it is analysed the timeline of the main future environmental issues and how they will affect the aviation industry. It is expected that environmental issues will predominantly affect infrastructure and operations (Table 4.29). However, some impacts may not be a concern until the middle of the century while others may be experienced sooner.

Atmosphere composition

To face the environmental issues mentioned previously, it is essential to have a better knowledge of the atmospheric composition in order to achieve better forecasts and predictions that would allow developing mitigation strategies. There are several initiatives and projects which are currently in development and they are expected to progress significantly in the long term. Their main methods to monitor atmosphere are based on satellite and airborne instrumentation. Some examples of these projects are described in the following sections.

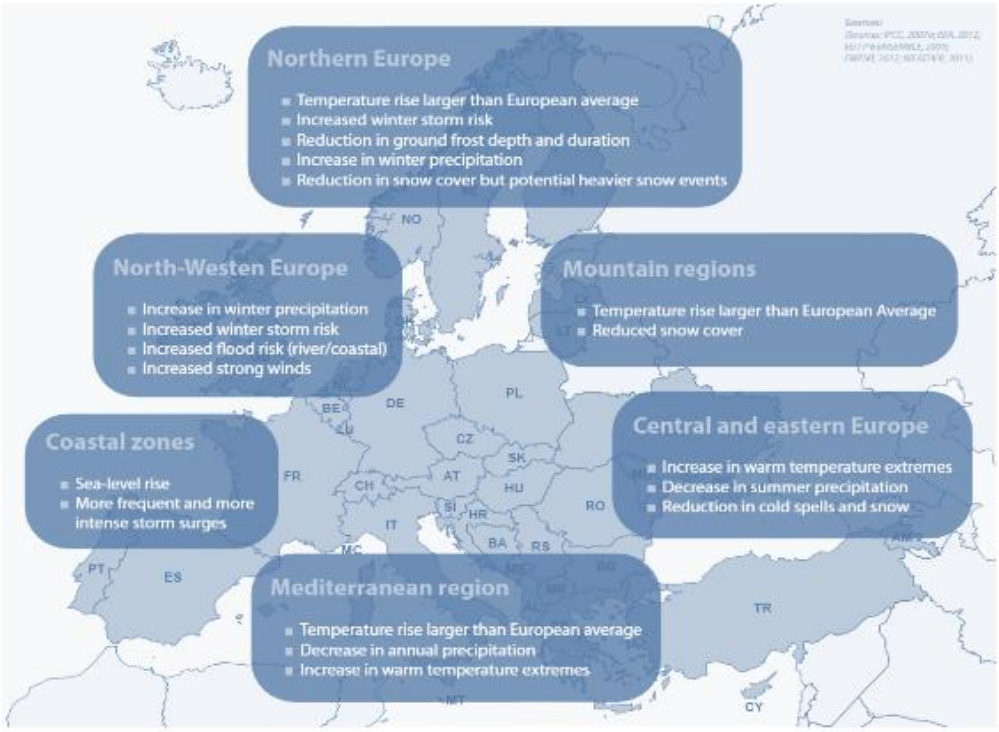


Figure 4.123: Environmental issues impacts on aviation by region

Satellite instrumentation:

- <u>Copernicus project:</u>

Copernicus is the European system for monitoring the Earth and it is coordinated and managed by the European Commission. It consists of a complex set of systems which collect data from multiple sources: earth observation satellites and in situ sensors such as ground stations and airborne sensors. It processes this data and provides users with reliable and up-to-date information through a set of services related to environmental and security issues. Copernicus: The Copernicus programme is supported by a dedicated constellation of satellites, known as “Sentinels”, which are specifically designed to meet the needs of the Copernicus services and their users. The first of these sentinels was launched in 2014 and it is expected to launch more satellites in the next years. Copernicus also draws on a large number of in situ (meaning on-site or local) measurement systems put at the disposal of the programme by the EU Member States. These include sensors placed on the banks of rivers, carried through the air by weather balloons, pulled through the sea by ships, or floating in the ocean. In situ data are used to calibrate, verify and supplement the information provided by satellites, which is essential to deliver reliable and consistent data over time.

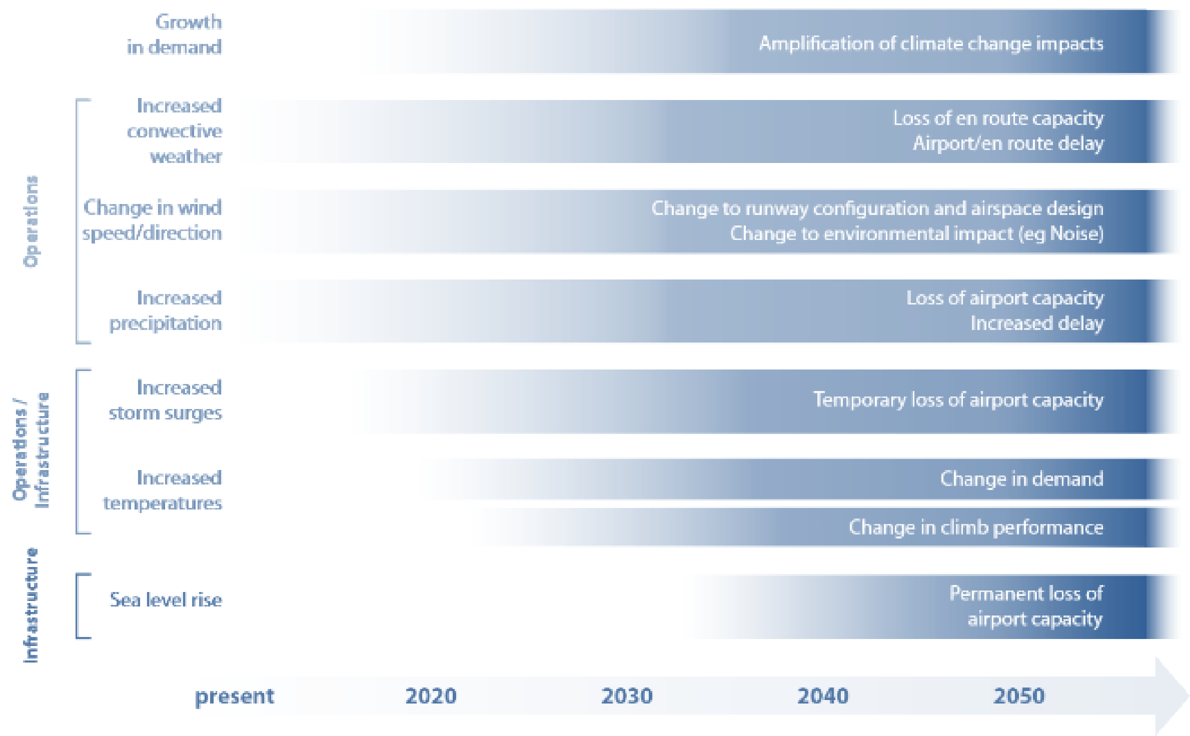


Table 4.29: Effects of climate change on aviation

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 4.124.

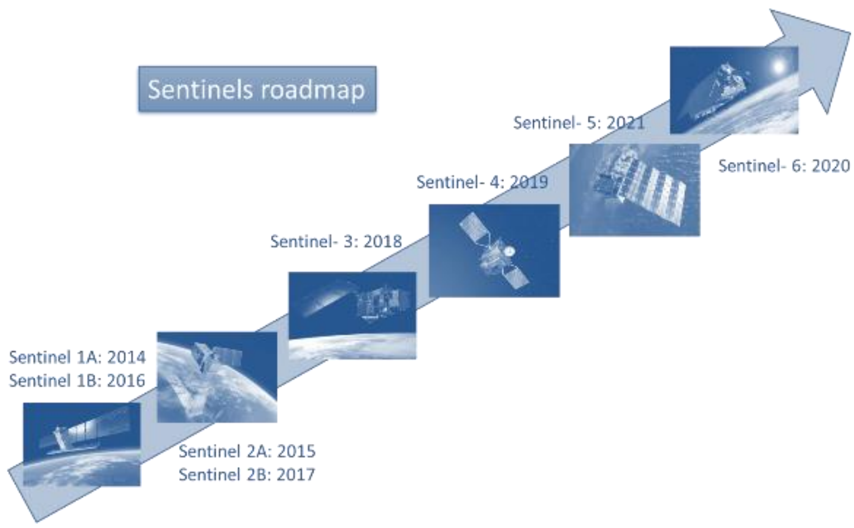


Figure 4.124: The Sentinel families of European environmental satellites

The Sentinel-1 mission is designed as a two polar-orbiting satellites constellation: Sentinel-1A, the first satellite that was launched on 3 April 2014 and Sentinel-1B which was launched on April 2016. Sentinel-1 is a radar imaging satellite which delivers images day and night under all weather conditions, for land and sea monitoring.

Sentinel-2 provides high-resolution optical imagery for land services. It provides, for example, the imagery of vegetation, soil and water cover, inland waterways and coastal areas. Sentinel-2 also delivers information for emergency services. The twin satellites Sentinel-2A and Sentinel-2B were respectively launched on June 2015 and on March 2017.

Sentinel-3 will provide high-accuracy optical, radar and altimetry data for marine and land services. It measures variables such as sea-surface topography, sea- and land-surface temperature, ocean-colour and land colour with high-end accuracy and reliability. The first Sentinel-3 satellite (S-3A) was launched in February 2016 and is supporting ocean forecasting systems, as well as environmental, agriculture and climate monitoring. A second satellite (S-3B) is scheduled for launch in 2018.

Sentinel-4 will provide data for atmospheric composition monitoring. Its objective is to monitor key air quality trace gases and aerosols over Europe at high spatial resolution with a fast (hourly) revisit time. It will be a payload embarked on EUMETSAT's Meteosat Third Generation (MTG), which is scheduled to be launched around 2019.

Sentinel-5 will also be dedicated to atmospheric composition monitoring. It will be a payload embarked on a EUMETSAT's Metop Second Generation (Metop-SG) to be launched in 2021 timeframe. It will provide accurate measurements of key atmospheric constituents such as ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide, methane, formaldehyde, and aerosol properties.

Sentinel-6 will provide high accuracy altimetry for measuring global sea-surface height, primarily for operational oceanography and for climate studies. It is a cooperative mission developed in partnership between Europe (EU, ESA and EUMETSAT) and the U.S. (NOAA and NASA). It is planned for launch in 2020, as shown in the Sentinel maturity plan (Figure 4.125).

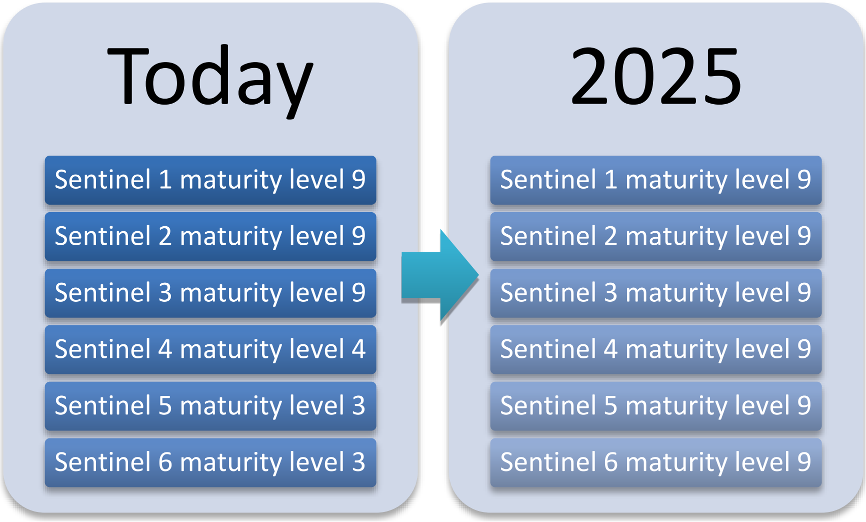


Figure 4.125: Maturity Plan for the Sentinel family.

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

Sentinels projection

- COSMIC mission

New research indicates that the COSMIC microsatellite system (Figure 4.126), which uses a technology known as GPS radio occultation to observe remote regions of the atmosphere, can significantly improve predictions of climate.

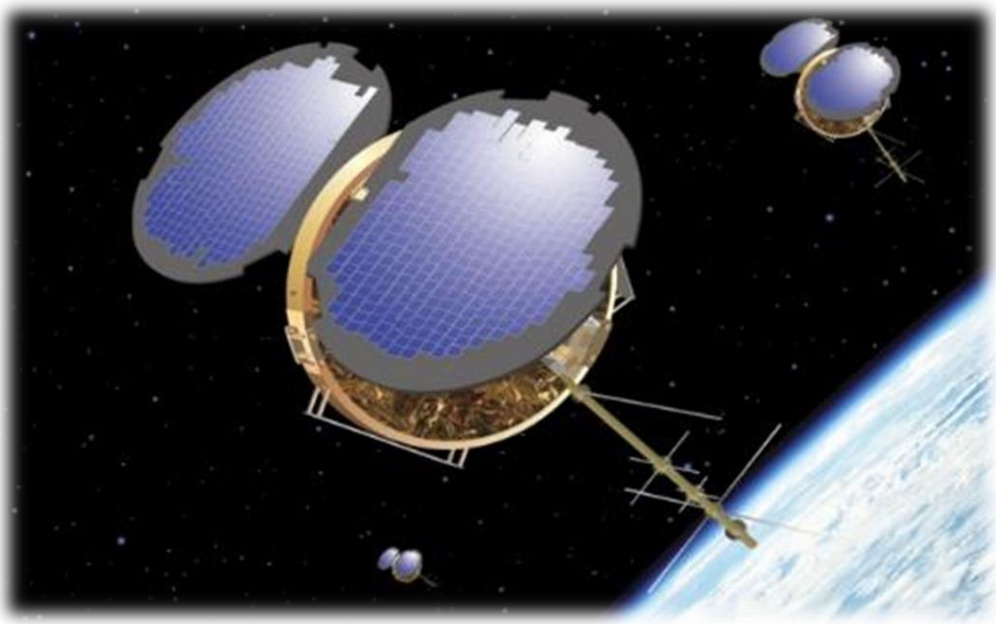


Figure 4.126: Cosmic microsatellite system

The COSMIC mission (Constellation Observing System for Meteorology, Ionosphere, and Climate) is a collaborative project between Taiwan and the United States to demonstrate the use of the radio occultation (RO) technique for weather prediction, climate monitoring, and space weather forecasting. The two countries plan to launch an additional six COSMIC satellites in 2016 and another six in 2018, which will give forecasters and researchers far more data.

Forecasts traditionally draw on observations taken by instruments on Earth's surface or by radiosondes, which are lifted into the atmosphere by balloons. But both these approaches are limited in hard-to-access places, like the open ocean. In contrast, GPS radio occultation measurements can be made almost anywhere, and they are unaffected by clouds, light rain, or airborne aerosols. By using GPS signals to monitor the atmosphere in three dimensions, the FORMOSAT-3/COSMIC satellite constellation has led to improved global weather monitoring, especially in data-sparse regions. This microsatellite system has proved its value, providing many applications for weather forecasting.

Applications:

Weather

- Improve global weather analyses, particularly over data-void areas (such as oceans and polar regions)
- Improve the skills of global and regional weather prediction models
- Improve understanding of tropical, midlatitude, and polar weather systems and their interactions

Ionosphere and space weather

- Observe global electron density distribution
- Improve the analysis and prediction of space weather
- Improve monitoring/prediction of scintillation and related phenomena (e.g., equatorial plasma bubbles, sporadic E clouds)

Climate

- Monitor climate change and variability with unprecedented accuracy and precision.
- Evaluate global climate models and analyses
- Calibrate infrared and microwave sensors

Data collected by COSMIC are especially useful for forecasting tropical cyclones, including typhoons and hurricanes. In addition, COSMIC is able to provide critical observations of water vapour, the fuel that drives tropical cyclones, in high vertical resolution, which means that scientists can determine how much water is present at what height in the atmosphere.

➢ Advanced Satellite Aviation Weather Products (ASAP)

The Advanced Satellite Aviation weather Products (ASAP) initiative has been developed to provide satellite-derived meteorological products and expertise to the Federal Aviation Administration (FAA) weather research community.

Research areas important to the aviation community that are addressed by the ASAP initiative include:

1. Convective Weather (Figure 4.127)

- Develop satellite-based information that will aid in the real-time now casting of convective initiation (CI) and the diagnosis of convection on meso-and synoptic scales.
- Develop a series of CI "interest fields" from existing satellite sensors that can help predict future convection on local scales (i.e., 1-4 km).
- Develop new methods for using hyperspectral data for accomplishing these goals.

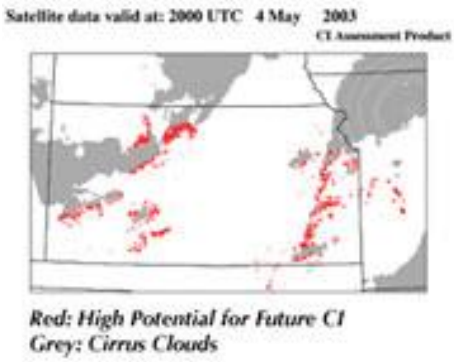


Figure 4.127: Convective initiation

2. Turbulence Detection (Figure 4.128)

- 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.

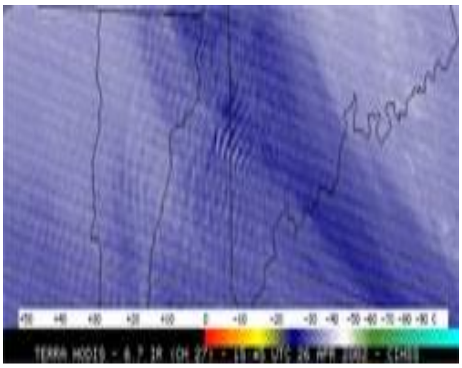


Figure 4.128: Turbulence Detection

3. Oceanic Weather (Figure 4.129)

- 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.

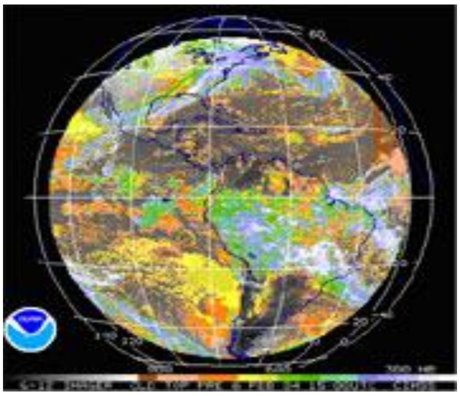


Figure 4.129: Oceanic Weather

4. Cloud Properties (Figure 4.130)

- 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.

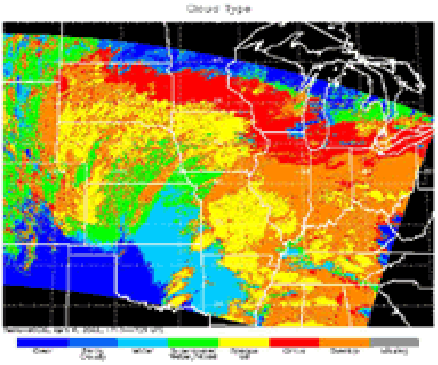


Figure 4.130: Cloud properties

5. Volcanic Ash (Figure 4.131)

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

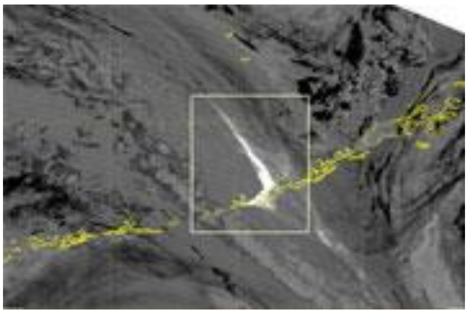


Figure 4.131: Volcanic Ash

6. Winds (Figure 4.132)

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

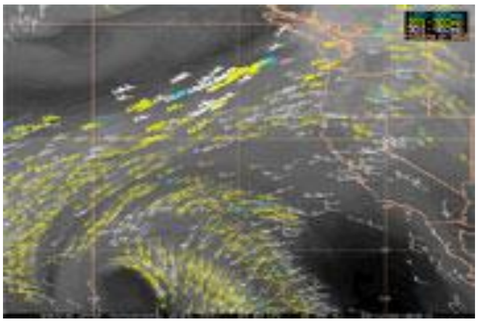


Figure 4.132: Winds

➢ EUMETSAT

EUMETSAT is the European operational satellite agency for monitoring weather, climate and the environment. It operates a system of meteorological satellites that observe the atmosphere and ocean and land surfaces – 24 hours a day, 365 days a year. This data is supplied to the National Meteorological Services of the organisation's Member and the Cooperating States in Europe, as well as other users worldwide. Its main objectives include identifying and monitoring the development of potentially dangerous weather situations as well as issuing timely forecasts and warnings to emergency services and local authorities, helping to mitigate the effects of severe weather. EUMETSAT operates a fleet of satellites in geostationary and polar orbit, being the Meteosat Second Generation (MSG) the satellites which are currently operative, providing images of the whole Earth, and data for weather forecasts. Some applications of these satellites are monitoring convective storms, volcanic ash clouds and the distribution and behaviour of fog.

EUMETSAT is planning and developing (Figure 4.133) 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 4.134) was fully approved by the EUMETSAT Member States in February 2011, thereby establishing the first pillar of EUMETSAT's future in the 2020-2040 timeframe. The MTG programme will revolutionise weather forecasting and environmental monitoring by providing a significant improvement over the capabilities of the current Meteosat generation. It should guarantee access to space-acquired meteorological data until at least the late 2030s. The Satellite Concept is based on:

- Four Imaging Satellites (MTG-I) (20 years of operational services expected)
- Two Sounding Satellites (MTG-S) (15.5 years of operational services expected)

Therefore, the satellite series will comprise four imaging and two sounding satellites. The imaging satellites, MTG-I, will fly the Flexible Combined Imager (FCI) and the Lightning Imager (LI), an imaging lightning detection instrument. The sounding satellites, MTG-S, will include an interferometer, the Infra-red Sounder (IRS), with hyper-spectral resolution in the thermal spectral domain, and the Sentinel-4 instrument, the high-resolution Ultraviolet Visible Near-infrared (UVN) spectrometer. Such improvements will allow better are spatial resolution and as a consequence, better predictions and forecasts.

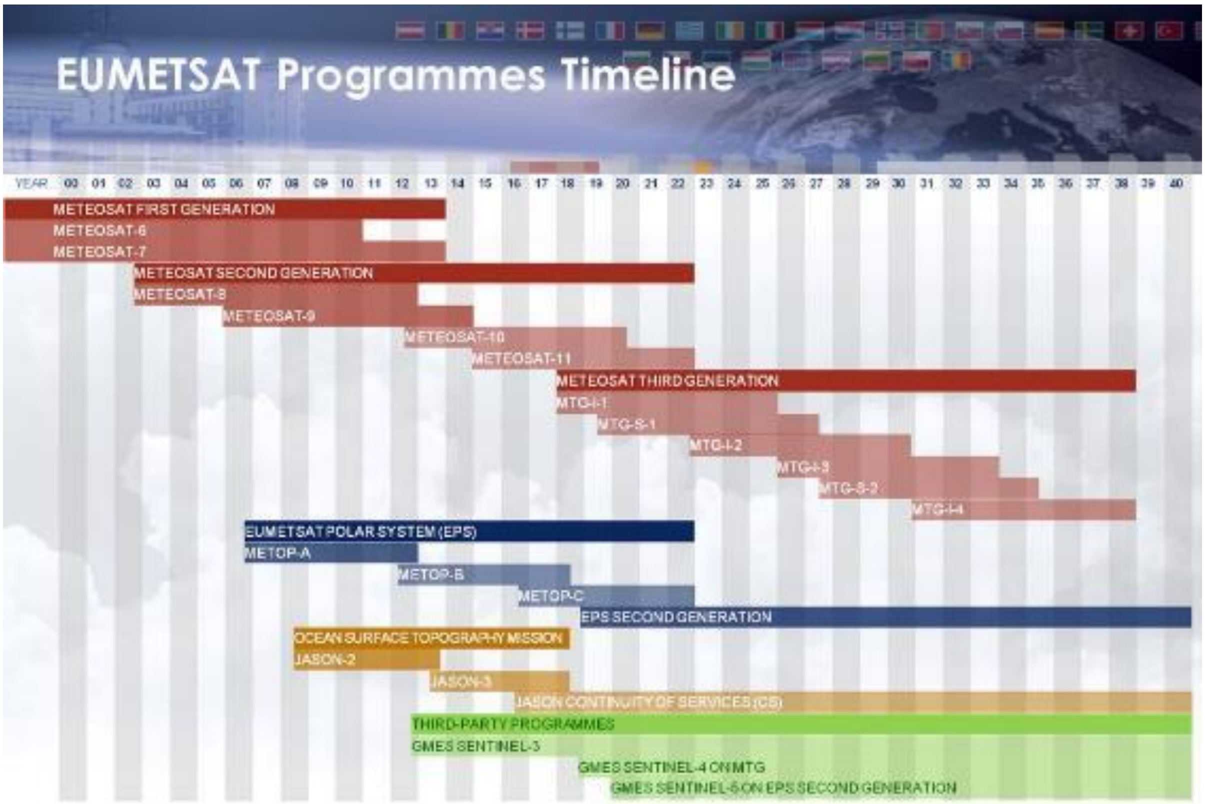


Figure 4.133: Successive generation of EUMETSAT

- <u>The EUMETSAT Polar System Second Generation (EPS-SG)</u> is the second pillar (Figure 4.135) 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 time frame. In the next image it can be seen the overview of EUMETSAT programs, with all the satellites programme launches:

Meteosat Third Generation Projection:

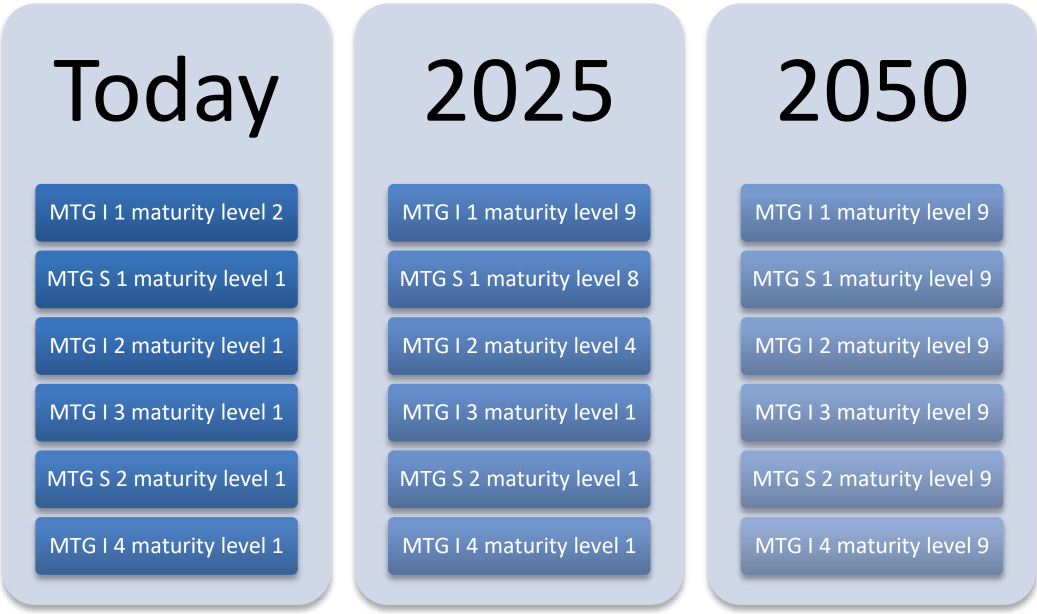


Figure 4.134: Meteosat Third Generation Satellite Maturity Plan

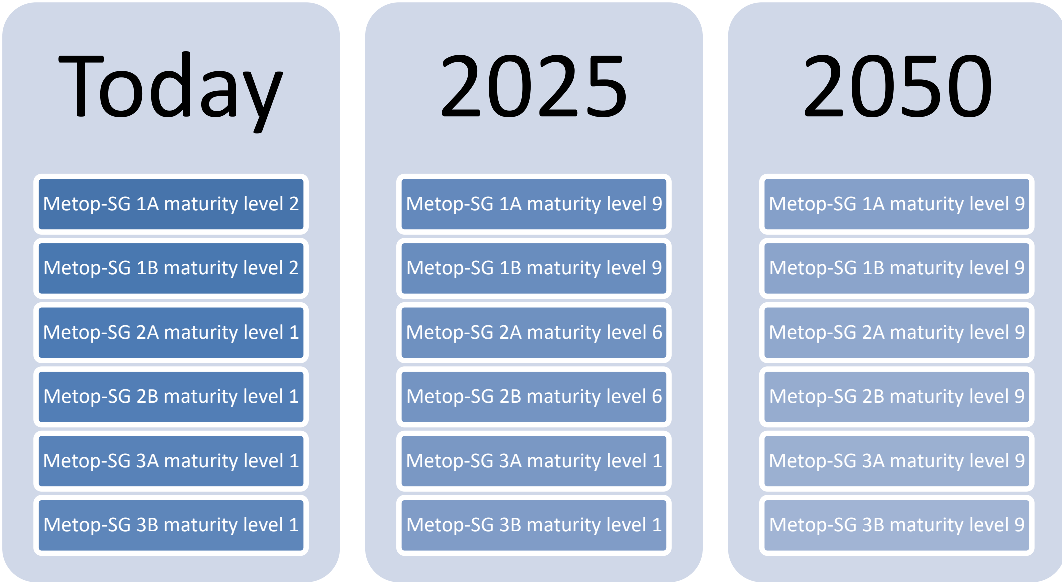


Figure 4.135: Polar System Second Generation (EPS-SG) Projection

In the next image (Figure 4.136), it can be seen the data that will be provided by monitoring satellites mentioned before:

Figure 4.136: Image obtained by several environmental satellite system

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 images (Figure 4.137), it can be seen examples of installation of IAGOS-CORE instrumentation aboard aircraft:

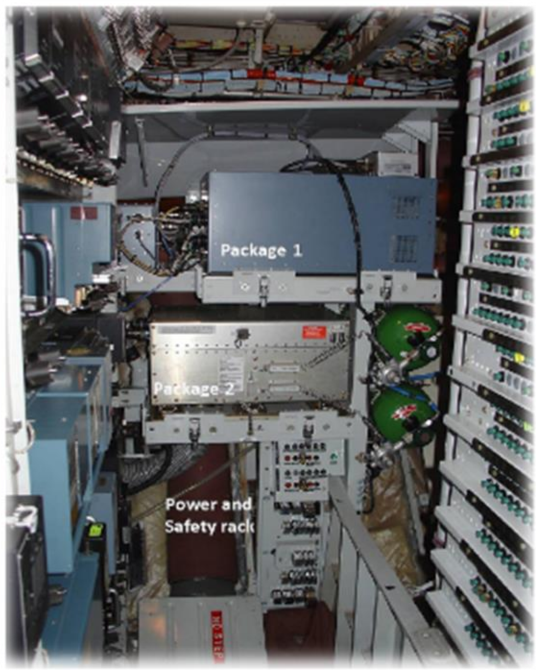


Figure 4.137: Instrumentation installed in aircraft for environmental purpose

At present time, eight aircraft are flying for IAGOS (one with IAGOS-CARIBIC and seven with IAGOS-CORE). Therefore, the technology for monitoring atmosphere through the onboard system already exists and the objective is to expand this technology. That is to say, the purpose of the future will be to increase the fleet of aircraft with this technology on-board. The long-term plan is to increase the number of aircraft to 20 in order to further enhance the geographical coverage. New instruments will be developed in response to future scientific and societal challenges.

Timeline Projection:

As technology has already been deployed, the corresponding TRL is number 9. Therefore, the projection which is represented below is the expansion of this technology. Taking into account that the current IAGOS fleet is 8 aircraft the projection could be as shown in Figure 4.138.

The IAGOS project is only one of several projects which use aircraft onboard systems to measure the atmospheric composition. In the future, the objective will be to **equipped aircraft** in a massive way with this type of instruments. In this way, the atmospheric composition measurement will be more accurate and reliability. In addition, one initiative of recent years is to use **drones** to measure atmospheric composition since a drone will be able to fly to any point in the vertical atmosphere and take air sample readings and transmitting them to a ground computer for monitoring. They could also be used on routes which aircraft normally do not use and provide atmosphere data closer to the ground. These two measures will suppose the main breakthrough in the future.

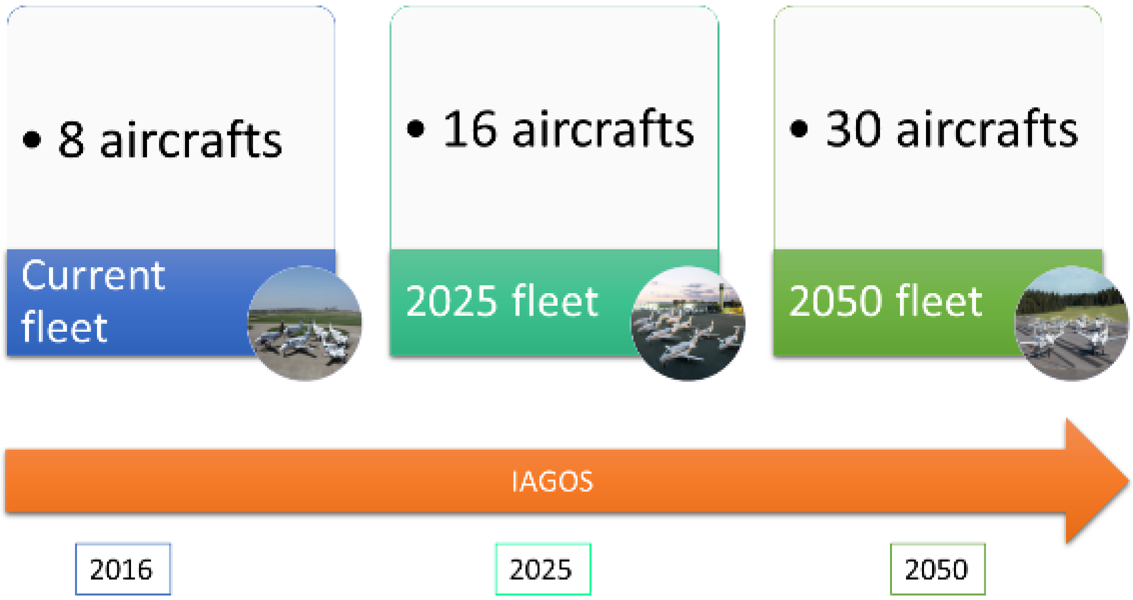


Figure 4.138: Expected growth in the size of the fleet of aircraft equipped with IAGOS instrumentation

Breakthrough measures to monitor atmosphere

In the future, three possible ways of development that could suppose breakthrough:

- Equipped aircraft in a massive way with instruments capable of measuring atmospheric parameters;
- Using drones to monitor the atmosphere;
- Alternative ways to measure atmospheric parameters (the weather company);

In the following sections are described the previous measures that could suppose breakthroughs in the way in which the atmosphere is monitored.

➢ Onboard instrumentation

The IAGOS project described previously is only one of several projects which use aircraft on-board systems to measure the atmospheric composition. However, as it was mentioned previously, the IAGOS fleet which is equipped with instruments to measure atmosphere parameters consists only of 8 aircraft at the present time, which is a very small number. However, the measurements taken by these aircraft have a great value to evaluate the atmosphere composition and to predict weather events. Therefore, massively equipping aircraft with this type of instruments could provide an important breakthrough in this study field since the atmospheric composition measurements will be more accurate and reliable.

In addition, the aircraft should have not only this type of equipment available but also a communication system capable of broadcasting in real-time the measures taken by this equipment to all the stakeholders. Therefore, it will be required on-board advanced communication systems capable of collecting all the relevant data from the atmosphere, processing and sharing it with all the actors. In this way, weather predictions and forecasts will be more accurate and efficient. Taking this into account, it will be necessary to assure the integrity, reliability and availability of the on-board communication systems.

➢ Unmanned aircraft systems (UAS)

The availability of high-quality atmospheric measurements over extended spatial and temporal domains provide unquestionable value to meteorological studies. Traditional methods related to atmospheric measures include remote sensing instruments (radars, lidars, sodars and radiometers) or in-situ probes carried by balloons or manned aircraft. An alternative to these traditional approaches is the acquisition of atmospheric data through the use of highly capable unmanned aircraft systems (UAS) working in coordination with weather radar systems and other observing stations and platforms.

At present time, there is a key information gap between instruments on Earth's surface and on satellites. UAS could solve that gap revolutionizing the ability to monitor and understand the global environment, by operating at a lower altitude than aircraft and collecting data from dangerous or remote areas, such as the poles, oceans, wildlands, volcanic islands, and wildfires. Better data and observations would improve understanding and forecasts allowing better anticipation to dangerous weather events.

The use of unmanned aircraft systems (UAS) or unmanned aerial vehicles (UAVs) has become the most promising technology in atmospheric monitoring over the last few decades. UAS have the potential to become a major resource for scientific research and weather monitoring as they are capable of flying to any point in the vertical atmosphere and take air sample readings. They could also be used on routes which aircraft normally do not use and provide atmosphere data closer to the ground.

The capabilities of UAS have increased dramatically over the past decade, especially with improvements in autonomous flight performance. Moreover, the ability to send a UAS on a mission without the need for a pilot greatly expands the potential for extended measurements while simultaneously lowering the operational costs.

UAS could measure meteorological state parameters, such as wind, temperature, humidity, turbulence and other variables with great accuracy as well as rates of variation of these parameters. Over the last few decades, government agencies and private sector companies have employed UAS for surveying and atmospheric research, including hurricane research and volcanic plume sampling. UAS use for meteorological and other environmental monitoring began in the 1990s and became routinely used in the 2000s. Through several missions, the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) have proved their capability to be operated routinely to obtain science-quality data over remote atmospheric regions.

One recent example is a small unmanned aircraft system which is being developed by Black Swift Technologies for research in extreme environments. This UAS called SuperSwift XT (Figure 4.139) has been designed to collect data in harsh environments and to carry out in situ observations from inaccessible regions. One of its uses will be to explore volcanoes in order to improve air traffic management systems and the accuracy of ashfall measurements. This drone will be compound by sensors specifically designed to measure selected gases and atmospheric parameters, including temperature, pressure, humidity and 3D winds, as well as more advanced measurements, such as particle sizing and trace gases.

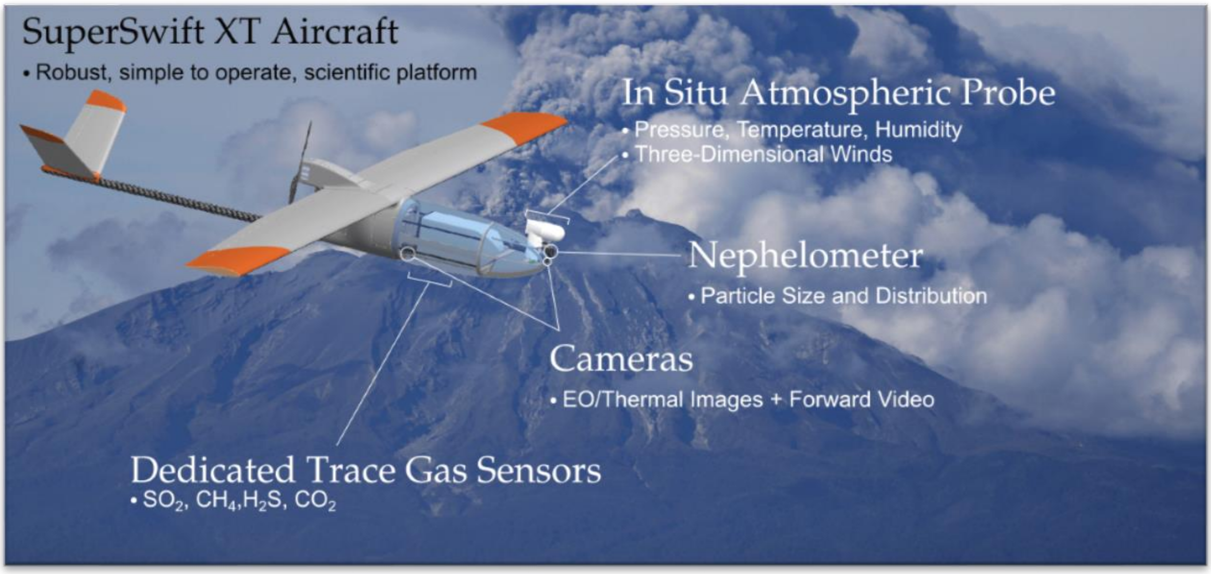


Figure 4.139: An UAV designed for environmental monitoring in hazardous conditions

The sensor and sensor coverage component will depend on the requirements of the systems and these requirements will depend on the application. A sensor will have to provide information about absolute, or process parameters at twice their natural temporal and spatial variability to ensure a representative natural data parameter field. Data processing architecture should be able to handle real-time, near terabyte per second data volumes, and data of multiple formats. It should also be able to accept and send secure communications. It will also require an onboard archive and ground station archive points to facilitate operational activities, ensure protection and minimize data loss.

In the following Table 4.29, 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 4.29: Capabilities expected of an UAV designed for environmental monitoring

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

- The drones will have to operate in airspace with other aircraft. Therefore, it will be necessary to develop procedures and rules so that both can operate without collision risks. For example, by the assurance of safe separation distances between unmanned aircraft and manned aircraft when flying in the national airspace;
- One of the unmanned aircraft main uses will be to operate in severe weather regions or in inaccessible areas. This will imply higher risks since they could suffer damage due to the severe conditions that will imply higher costs.

Due to a large amount of communications and data, unmanned aircraft could be exposed to security threats. Therefore, it will be required to assure data integrity and quality, data information dissemination and storage.

Despite the risks mentioned previously, using unmanned aircraft to monitor the atmosphere will have a lot of benefits that will allow developing better weather prediction models and forecasts. Although UAS are deployed operationally worldwide, they have not been integrated yet in weather monitoring operations at the present time. Using these systems on a global scale could support a great breakthrough in atmosphere monitoring. This is because as these systems become more common, it would allow to improve significantly weather modelling and forecasting.

➢ Cognitive intelligence for weather prediction: The weather company.

Using data from commercial aircraft and mobile phones to measure atmospheric parameters closer to the ground have been one of the most revolutionary ways to monitor the atmosphere in recent years. It has allowed disposing of more data to develop better weather predictions. This initiative has been carried out by the Weather Company.

The Weather Company is a weather forecasting and information technology company, which provides the world's leading technology platforms and services leveraging weather and related data. It provides critical weather information to a variety of business industries: aviation, energy, insurance and utility, as well as visualization software for broadcast media and digital platforms.

In addition, the company delivers critical weather data from around the globe to airlines worldwide, producing 26 billion individual forecasts daily. Meteorological insights are drawn from satellites, weather stations, planes, radar, terminal and 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 4.140) 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.

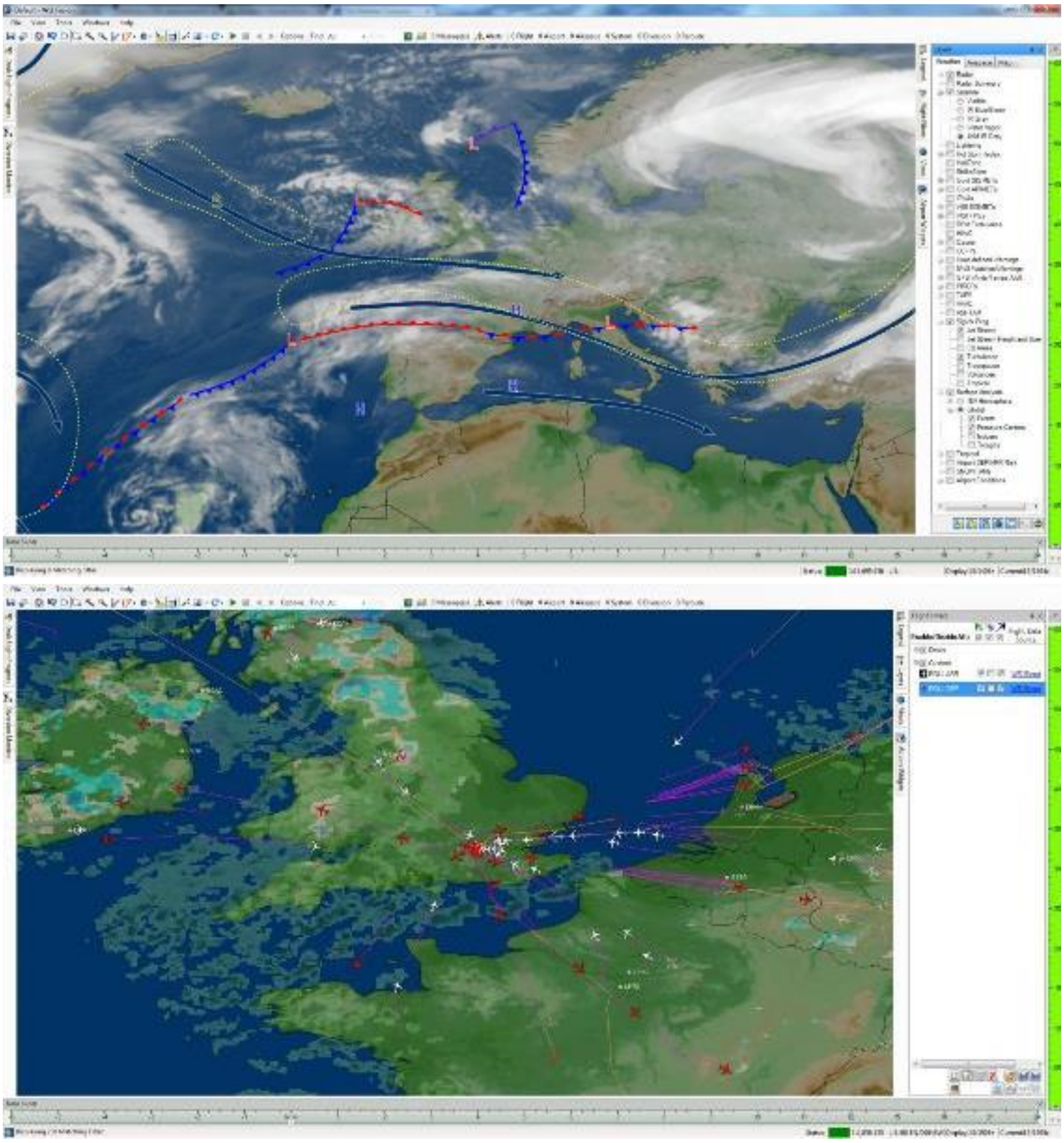


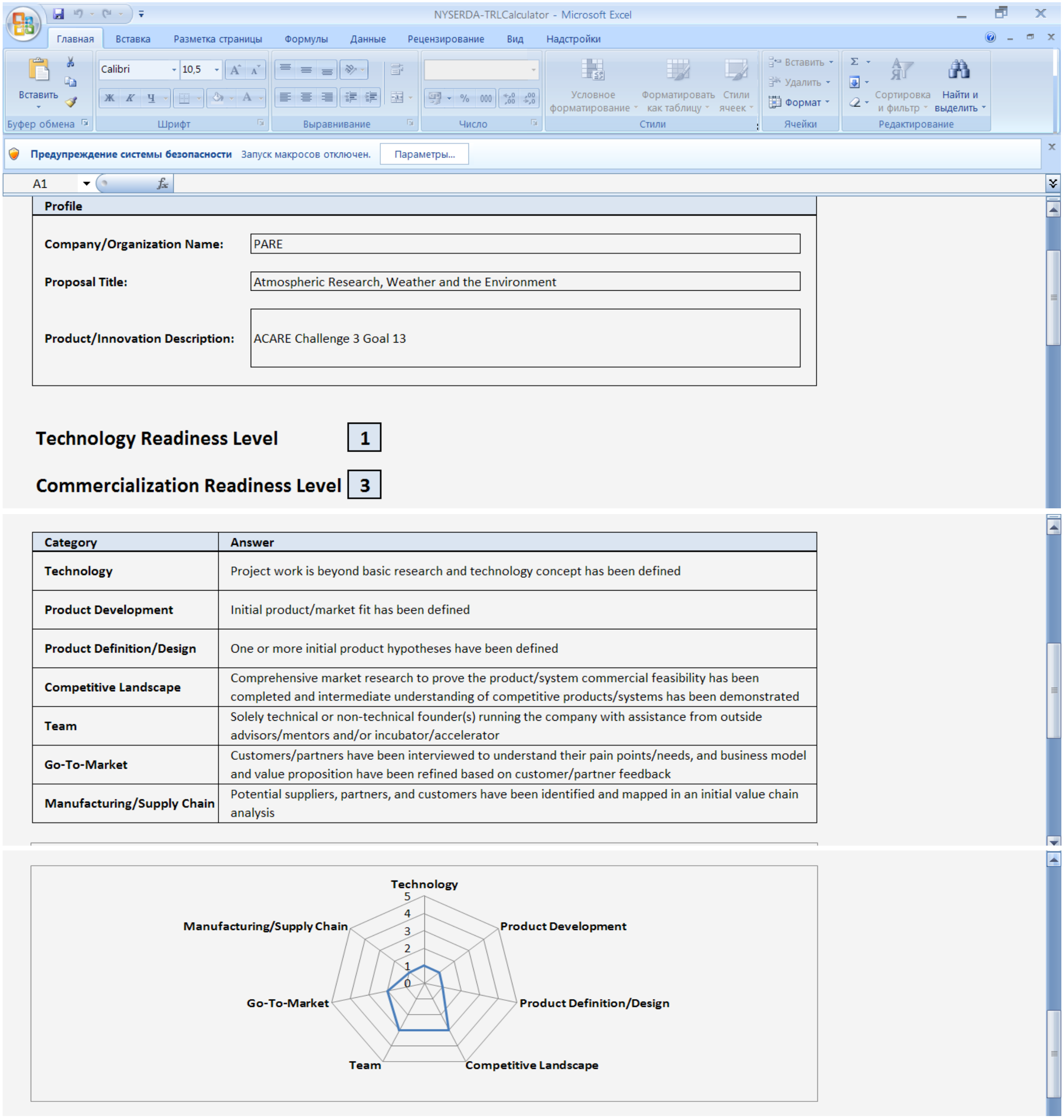
Figure 4.140: Weather alert available for aviation

By applying these techniques, it has been obtained beneficial results. For one airline using WSI Total Turbulence they experienced:

- A 50% reduction in Flight Attendant injuries;
- Year over year reduction in maintenance (40%);
- Captains accepting a higher number of planned flights;
- A decrease in turbulence encounters.

In conclusion, this type of weather forecasts will suppose a breakthrough in technology which will be enhanced in the future and it will allow developing better prediction models, decreasing damages caused to aviation due to weather conditions.

NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 13** "Atmospheric Research, Weather and the Environment" achievements at 1st stage of the researches on PARE Project are shown in Figure 4.141 grounding on the results of the 1st year PARE report (PARE D1.1, 2018).



NYSERDA-TRLCalculator - Microsoft Excel

Profile

Company/Organization Name:	PARE
Proposal Title:	Atmospheric Research, Weather and the Environment
Product/Innovation Description:	ACARE Challenge 3 Goal 13

Technology Readiness Level 1

Commercialization Readiness Level 3

Category	Answer
Technology	Project work is beyond basic research and technology concept has been defined
Product Development	Initial product/market fit has been defined
Product Definition/Design	One or more initial product hypotheses have been defined
Competitive Landscape	Comprehensive market research to prove the product/system commercial feasibility has been completed and intermediate understanding of competitive products/systems has been demonstrated
Team	Solely technical or non-technical founder(s) running the company with assistance from outside advisors/mentors and/or incubator/accelerator
Go-To-Market	Customers/partners have been interviewed to understand their pain points/needs, and business model and value proposition have been refined based on customer/partner feedback
Manufacturing/Supply Chain	Potential suppliers, partners, and customers have been identified and mapped in an initial value chain analysis

Figure 4.141: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 13** "Atmospheric Research, Weather and the Environment"