UDC 629.7: 534.2

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PARE preliminary analysis of ACARE Challenge 3 environmental impact goals (towards quiter and cleaner environment in aviation sector)

Aviation is recognised as one of the top advanced technology sectors in Europe and generates innovation that benefits society at large far beyond its direct operational sphere. There are growing concerns about the impact of aviation on the atmosphere with respect to noise, local air quality (LAQ) and the associated human health and welfare impacts. Meeting community expectations on aircraft noise, engine emission and fuel/energy consumption has always presented a challenge to aircraft and engine manufacturers and to those involved in airport planning and air traffic management.

PARE - Perspectives for the Aeronautical Research in Europe.
The overall objective of PARE (EU H-2020 project “Perspectives for the Aeronautical Research in Europe”) is to trigger collaboration between European stakeholders to support the achievement of the 23 ACARE *Flightpath 2050* goals [1], by providing yearly reports (and respective methodology) that assess the progress, gaps and barriers and propose suitable measures to close the remaining gap [2]. PARE’s concept (Figure 1) is based on the need to:

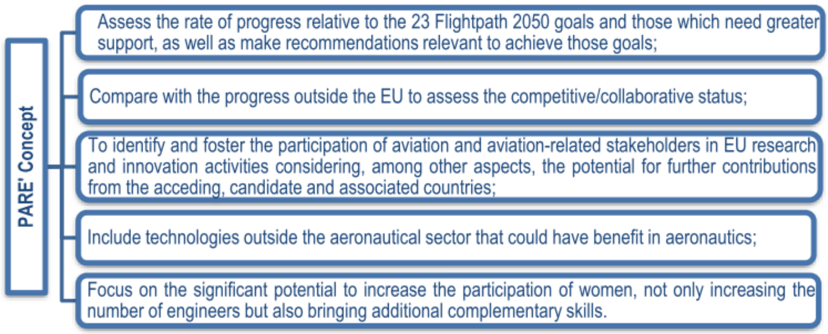

Figure 1. Needs addressed through PARE’s concept [2]

Aviation is recognised as one of the top advanced technology sectors in Europe and generates innovation that benefits society at large far beyond its direct operational sphere. It provides close to twelve million skilled jobs, directly and indirectly, and contributes over 700 billion euros to Europe’s gross domestic product [3]. Home to some 400 airlines and nearly 700 airports, European aviation plays a key role in serving society’s needs for safe, secure and sustainable mobility in Europe and all over the world. Its impact on the wider European economy is significant and must be sustained.

The leadership of Europe in the field of aviation is underpinned by a commonly shared vision and a globally acknowledged research agenda. Ten years ago the Advisory Council for Aeronautics Research in Europe (ACARE) was established to provide dedicated and independent advice on strategic issues affecting the sector [4]. The preparation of the Strategic Research Agenda in 2001, following the publication of Vision 2020, is a prime example of the work this body has performed. ACARE has developed a strategic research and innovation agenda (SRIA) to meet the challenging goals set by *Flightpath 2050* (Figure 2). The ambitious goals of *Flightpath 2050* remain valid to deliver two aims: firstly to serve society's needs for safe, more efficient and environmentally friendly air transport; and secondly, to maintain global leadership for Europe in this sector with a competitive supply chain and competitive operators. Research and innovation in aviation is the key to tomorrow's mobility and prosperity as well as environmental and energy challenges.

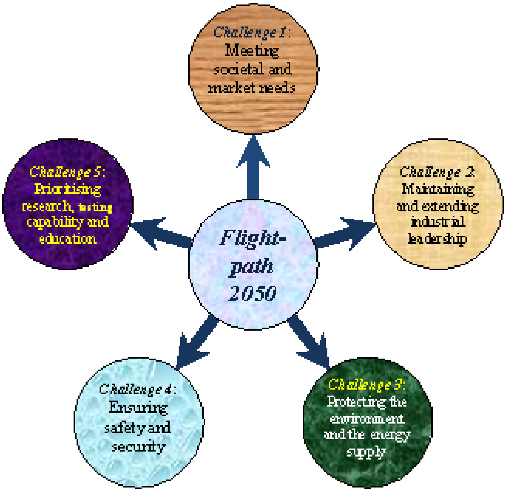

Figure 2: Key challenges of a strategic research and innovation agenda *Flightpath 2050*

The local environment agenda for aviation is driven largely by noise and occasionally by local air quality impacts, whereas the national and international agenda is primarily focussed on climate change and carbon dioxide emissions. In carrying out its responsibilities, ICAO and its Member States will strive to limit or reduce these dominant and prioritised impact factors, mostly without quantified values and being more qualitative, providing the States and/or their Unities to formulate their goals in accordance with their achievements in science and technology (Table 1). Meeting community expectations on aircraft noise, engine emission and fuel/energy consumption has always presented a challenge to aircraft and engine manufacturers and to those involved in airport planning and air traffic management. To achieve these targets, all (governmental and industrial) stakeholders agreed to closely work together along a four-pillar strategy:

- *Improved technology*, including the deployment of sustainable low-carbon fuels;
- More *efficient aircraft operations*;
- *Infrastructure improvements*, including modernized air traffic management systems;
- *Actions* within the aviation sector *to adapt and develop resilience* to the current and future impacts of climate change
- A *single global market-based measure*, to fill the remaining emissions gap.

Table 1: Comparison of long-term goals for environmental impact factors of aviation between ICAO Policy, EU and USA Research and Development agenda

Environmental impact factor from aviation	**ICAO Policy Goals [5]**	**EU ACARE Goals** (*FP2050* till 2050)	**US FAA and NASA Goals** (*NSTC2010* [6] and *CLEEN II* [7] till 2035)
Noise	***Limit or reduce the number of people affected*** *by significant aircraft noise*	perceived noise emission of flying aircraft ***is reduced by 65%***	***52 dB reduction*** relative to cumulative margin of ICAO/FAA Stage 4 noise limit (a 25-year goal, by enabling N+3 aircraft and engines)
NO_x emissions	***Limit or reduce the impact of aviation emissions*** *on local air quality*	***90% reduction*** in NO_x emissions	**80%** ***reduction*** in NO_x emissions (for cruise relative to 2005 best in class and for LTO relative to ICAO CAEP/6 standard)
Greenhouse gas emissions and fuel/energy consumption	***Limit or reduce the impact of aviation greenhouse gas emissions*** *on the global climate*: a ***reduction in net aviation*** CO_2 ***emissions of 50%*** by 2050, relative to 2005 levels	***75% reduction in*** CO_2 ***emissions*** per passenger kilometre	***60% reduction in Aircraft Fuel/Energy Consumption*** (*CO_2 emissions per passenger kilometre?)* relative to 2000 best in class

ACARE has developed a comprehensive roadmap to deliver the *Flightpath 2050* goals (for the key challenges shown in Figure 2), and as part of this it will continue to foster the need to monitor achievements and progress on the SRIA objectives. As an example, in 2015 the ACARE working group on energy and environment estimated that EU aviation sector had secured an overall 38% reduction in CO_2 per passenger-kilometre against a goal of 50% reduction goal for 2020. Similarly, technical solutions showed a potential reduction of 37% in perceived noise has been achieved against a goal of 50%, also by 2020. Whilst this represents significant progress, effort must be further strengthened to meet the even more challenging goals for CO_2, noise and NO_x emissions set for 2050 [3].

Research and innovation for evolutionary aircraft development 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. It is also essential that such technology roadmap and its implementation must continue to receive support through government policy and that it remains a priority for European society (Figure 3). 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 [3]. 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.

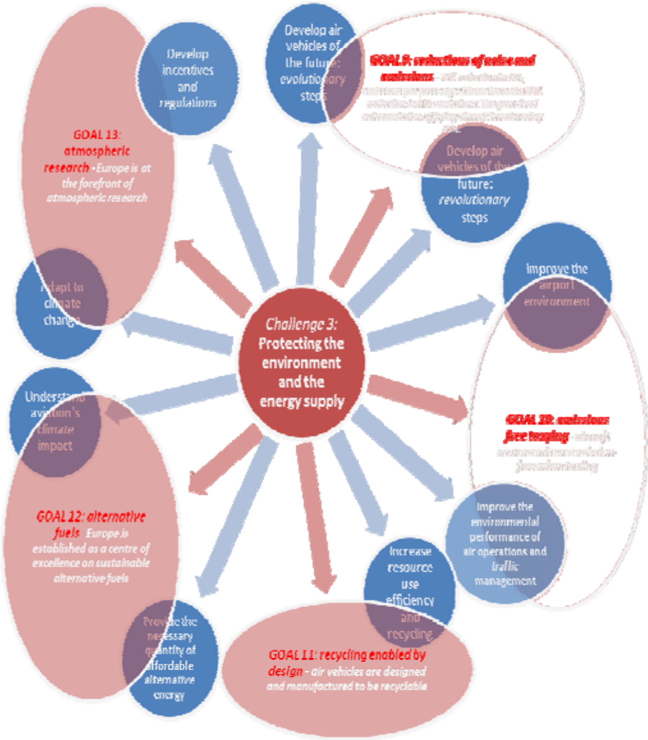

Figure 3: The goals and action areas for *Challenge 3* of the ACARE perspectives

Flight traffic scenario till 2050

In 2017 growth dynamic comes on top of Europe's airports having already welcomed an additional 300 million passengers between 2013 and 2016. EU airports alone contributed to more than 20% of global air traffic growth. This is as much as Chinese airports, and much more than US airports (which only accounted for about 12%). Such growth will not be linear, for instability is set to remain a defining feature of the years to come – both politically and economically. But one thing looks now certain: it will come with unrelenting capacity pressures upon airports.

Flight counts still below peak, but could see a 45% increase by 2035. Five years ago, flights had just seen a double-dip decline and were still 5% below the 2008 peak. So there seemed a need to reassure readers of the Challenges of Growth 2013 summary report ([8], p8) that, when economic growth returned, so would growth in air traffic (Figure 4). Strong and broad-based traffic growth in 2017 across all market segments finally took European flight totals over the 2008 peak, to 10.6 million [9]. Indeed, even 4% growth in flights in 2017 looks modest compared to almost twice that reported for passengers or passenger-km. Current growth is certainly supported by strong demand. This growth has brought traffic back to the most-likely scenario from the 2013 forecast (Figure 4).

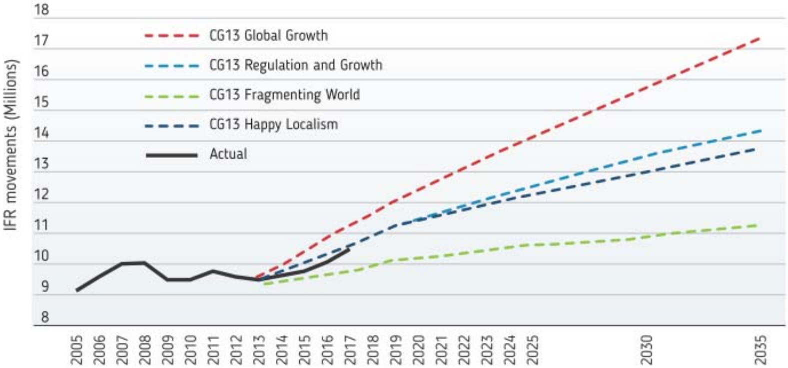

Figure 4: In 2017, strong growth saw traffic back on the most-likely scenario from the 2013 forecast [9]

ICAO predicts that the global passenger fleet will continue to grow at between 4% and 5% per year globally. The number of passenger aircraft, which is estimated to reach 29,000 in 2020, will increase to 58,000 in 2040. Freight traffic will grow at an even faster rate. The UK Department for Transport (DfT) predicts that the annual growth of aircraft operations within the UK will be of the order of 1-2% from 2010 and 2020 [10]. The rate at which the fleet will transition from the current fleet, to ‘imminent aircraft’ and to ‘future aircraft’, will depend upon the economic and commercial environment. An industry best estimate of fleet transition until 2050, based on growth data from DfT, is shown in Figure 5.

Newer aircraft and engines are more environmentally efficient, so the age of the European aircraft fleet is an important indicator. The mean aircraft age (weighted by the number of flights made by each aircraft) has crept up from 9.6 to 10.3 years, with only 2009 and 2010 seeing reductions. These reductions were driven by the rapid expansion of the low-cost fleet, which is younger than average, and retirements of less fuel-efficient older aircraft by the traditional scheduled operators in response to higher fuel prices and falling demand (retirements jumped to over 6% of the fleet per year in 2008 and 2009). This overall noise reduction is due to technological improvements, fleet renewal, increased ATM efficiency and the 2008 economic downturn. Fleet renewal has led to a 12% reduction in the average noise energy per operation between 2005 and 2014.

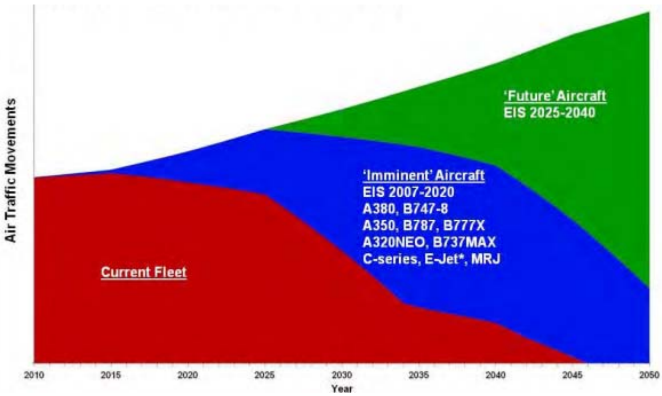

Figure 5: Predictions of Fleet transition from current aircraft to imminent and future aircraft 2010-2050 [11]

In parallel with an evolution largely driven by global environmental issues, there is evidence of increased sensitivity to noise in local communities impacted by aviation operations despite significant reduction of aircraft source noise over the years. Continued efforts may stabilize noise exposure by 2035 but it will continue to be a key challenge. Noise exposure has stabilized over the past ten years. The total population inside the STAPES L_{den} and L_{night} contours decreased by only 2% (L_{den}) and 1% (L_{night}) between 2005 and 2014, to reach 2.52 and 1.18 million people respectively in 2014 (Figure 5). Continuous improvement in aircraft noise performance has occurred over time across various weight categories. Work during the ICAO CAEP work programme from 2010 to 2013 included a review of noise technology goals by independent experts (IE) for the intermediate (2020) and long-term (2030) timescales [12]. The goals indicated in Table 2 for 2020 and 2030 provide a reference for potential future developments and are combined with existing aircraft data for the same weight categories (namely Regional Jets **RJ**, Short/Medium Range two-engine aircraft **SMR2**, Long Range two-engine aircraft **LR2** and Long Range four-engine aircraft **LR4**) over the period 1960 to 2015. Figures 6 and 7 shows the US and EU "technology only" goals harmonized to TRL6 and a common metric. Their respective baselines and noise reduction target versus US and European research goals are also identified.

Local Emissions of CO_2 and NO_x

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

Table 2: CAEP IEP2 Aircraft Noise Goals for short-medium (2020) and long (2030) term [13]

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

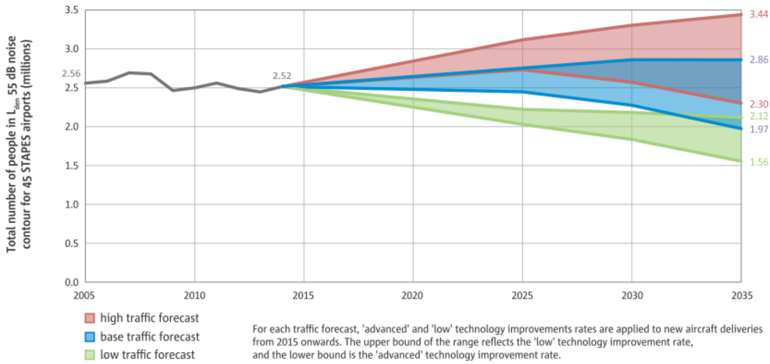

Figure 5: Future technology improvements could stabilize overall aircraft noise exposure in the 2035 timeframe [18]

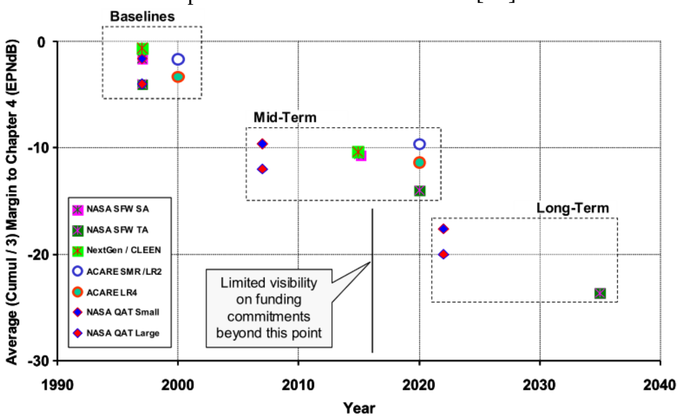

Figure 6: Comparison of US and EU research goals

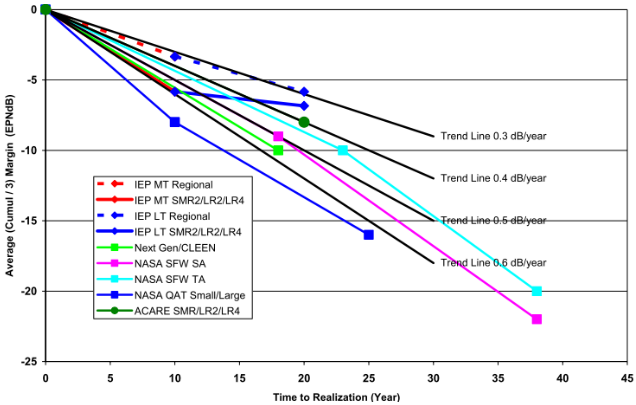

Figure 7: IEP2 predicted noise reduction target versus US and European research goals [12]

The first of the ICAO 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 year and 20 year time horizons.

The goals can be seen in the Figure 8, 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.

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

The Figure 9 provides a summary presentation of the test data results received for this review with the two types of combustor identified separately; the data points coloured grey being for RQL combustors, and those in red being for the new staged-DLI combustors. As with the first review, the conclusion reached was that RQL combustors appear likely to meet the MT goal, though a significant challenge remains, but the LT goal may not be achievable particularly for high OPR engines. Dramatic reductions in NO_x production from the use of new generation staged DLI combustors were in line with the expectations recorded in the 2006 Report, although the migration towards the LT goal was not expected so soon. However, the wide spread of NO_x performance raised questions about how such families of engines might be handled in the future within a goals setting process.

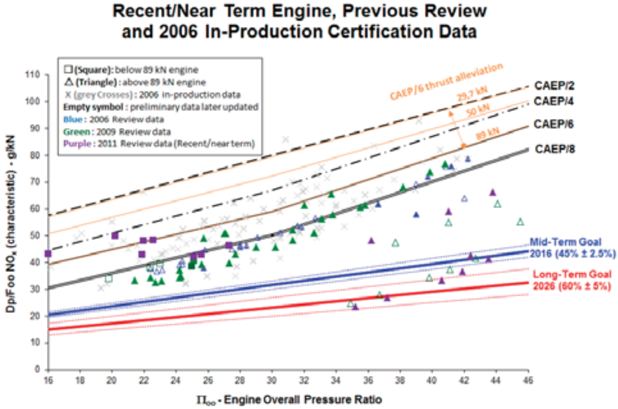

Figure 8: Historical ICAO certification Standards together with the 2006 MT & LT goals [17]

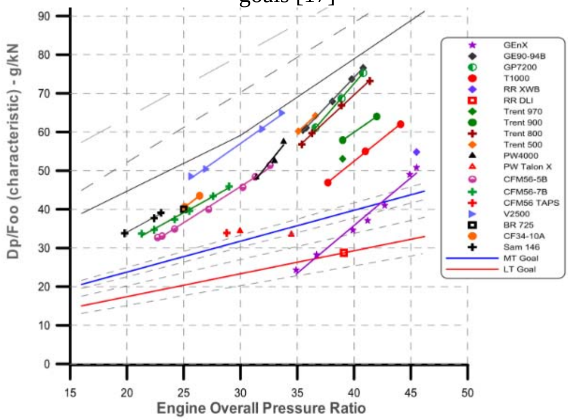

Figure 9: 2009 Review data with RQL combustors in grey and new mid-OPR engines. Generation staged DLI combustors in red [17]

Good progress has been shown on state of the art Single Annular Combustors with rich burn (air blast) injection, Double Annular Combustors/Axially Staged Combustors (rich pilot / rich main) and Lean Burn Combustors. The latest state-of-the-art lean burn fuel injection systems with centrally integrated pilot fuel injection for flame stabilisation have achieved up to 70 to 75% of NO_x reduction at TRL3 (demonstrated in a high pressure single sector combustor test rig) relative to the CAEP/2 certification standard. A technology deterioration factor, which describes the transition from TRL3 to TRL6 needs to be considered, leading to likely technological progress by the end of Framework 7 of a range of approximately 60 to 65% NO_x reduction. It is most likely that in Framework 8, research initiatives will need to focus on further improvements towards 70 to 85% NO_x reduction, which may lead to another 50% relative NO_x reduction and to higher Technology Readiness Levels [16].

Climate impact – CO2 emission and fuel consumption

The Figure 10 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 11 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.

The fuel burn analysis considers the contribution of aircraft technology, improved air traffic management, and infrastructure use (i.e., operational improvements) to reduce fuel consumption. The Figure 11 also illustrates the fuel burn that would be expected if ICAO's 2 per cent annual fuel efficiency aspirational goal were achieved. The trends presented in the Figures 10 and 11 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 Figure 12 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.

FORUM-AE's reference when assessing European progress towards ACARE emissions CO_2 & NOx goals is shown in the Figure 13. One should also note that NO_x emissions are considered either at local level when addressing air quality concern or at global scale when addressing climate change. Still referring to SRIA Vol. 1, Appendix, the timing assumption to progress towards CO_2 & NOx goals is the following [15].

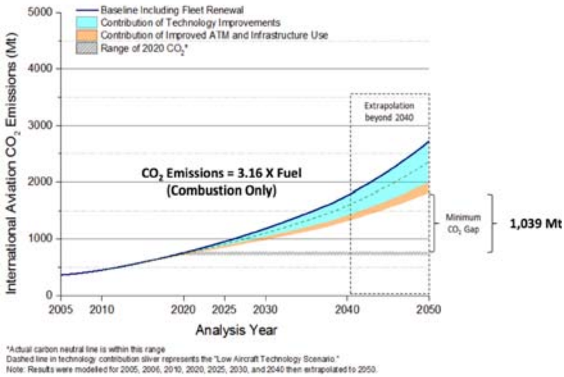

Figure 10: CO_2 Trends from International Aviation, 2005 to 2050 [18]

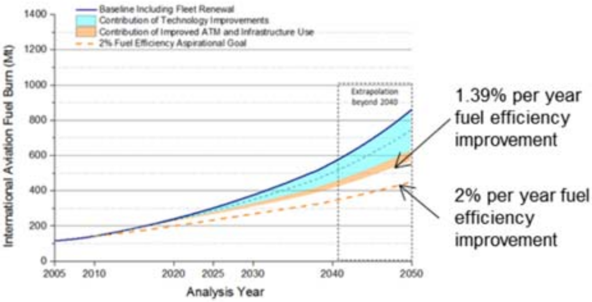

Figure 11: Fuel Burn Trends from International Aviation, 2005 to 2050 [18]

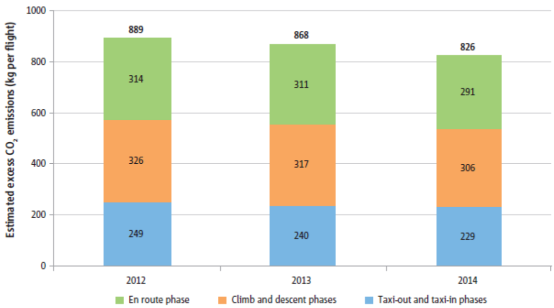

Figure 12: Estimated excess CO_2 emissions per flight are decreasing in taxi, take-off, climb/descent and en route phases [15]

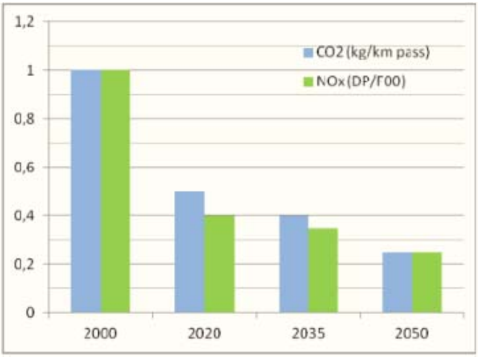

Figure 13: ACARE CO_2 & NOx goals calendar (using CAEP6 margin for NOx) [15]

Air traffic CO_2 share will keep increasing unless adapted measures are taken. ACARE 2050 ambitious objectives would permit to mitigate the increase of aviation part in anthropogenic CO_2. If ACARE technology goals were not achieved, if technology improvements were not introduced in the fleet early enough, and if global anthropogenic CO_2 was not growing as much as assumed, share of aviation could be above 5% in 2050. ACARE 2050 very challenging 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 in order to progress towards this ambitious goal.
Current and future technological developments to achieve the challenging ACARE 2050 CO_2 goal are essential to mitigate substantially the increase of aviation CO_2, with realistic traffic growth assumption (Figure 14). A large part of the effort of the last decade was supported within Clean Sky, and within other European projects like LEMCOTEC, ENOVAL and E-BREAK.

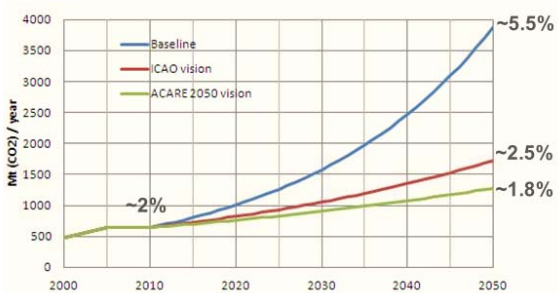

Figure 14: Global aviation CO_2 forecast with ACARE assumption [18]

A new assessment was performed against ACARE CO2 and NOx goals and is summarized in the following Table 3. Although, there is no ACARE objective related to ultrafine particles, this is now a key environmental and regulatory concern, which requires appropriate mitigation solutions (combustor technology and fuel composition).

Table 3: FORUM-AE assessment against ACARE emissions goals [15]

	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

Conclusions: *Preliminary TRL assessment for Goal 9 of Challenge 3*
NYSERDA (TRL/CRL) Calculator results for analysis and assessment of **ACARE Challenge 3 Goal 9** “Reduction of Noise and Emissions” (middle term goals) achievements at 1st stage of the researches on PARE Project are shown in Figure 15 grounding on the results of the 1st year PARE report.

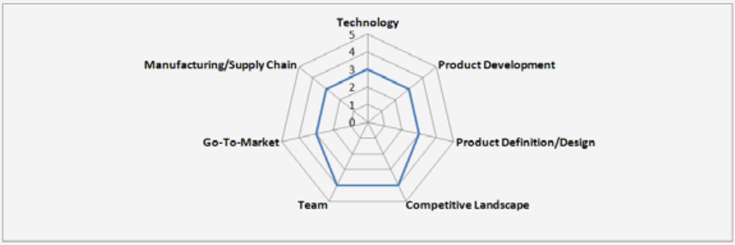

Figure 15: NYSERDA (TRL/CRL) Calculator results for analysis and assessment of ACARE Challenge 3 Goal 9 (middle term) “Reduction of Noise and Emissions”

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