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Fulfilling long-term emission reduction goals in aviation by alternative fuel options: An evolutionary approach

Ploetner, Kay Olaf; Urban, Marcia; Habersetzer, Antoine; Roth, Arne;
Bauhaus Luftfahrt e.V., Willy-Messerschmitt-Str. 1, Taufkirchen, 82024, Germany

Tay, Gilbert;
Technische Universität München, Boltzmannstr.15, Garching b. München, Germany

The forecasted growth of aviation in the next 20 years will most probably outpace fuel consumption reduction efforts on aircraft, air traffic management and airport level. By simulating the fuel reduction potential of new aircraft programs applying more evolutionary technologies with shortfalls of -20% to -50% of mission fuel per seat compared to the Flightpath 2050 goals lead to a reduction of the global, fleet-level fuel burn of -20% in 2035 and -46% in 2050 compared to a "No Action" scenario. Comparing these results with the ATAG goal, the aviation industry has to offset resulting emissions of around 124 Mt of fuel burn in 2035 accounting for roughly 35% of the overall fuel burn and further increasing beyond 2035. A large amount of alternative fuel with low CO_2 footprint is required which will require large investments to increase the production capacity. To close the CO_2 gap, the study focused on three conversion families for sustainable alternative fuels: 1) hydroprocessing of oils and fats (HEFA), 2) thermochemical conversion of biogenic (mainly lignocellulosic) feedstock, and 3) Power-to-Liquid. A basic sustainable alternative fuel production ramp up scenario showed that substantial efforts have to be taken by the aviation industry, especially during the years 2030-2045. In this scenario, an offset of CO_2 by sustainable aviation fuels would require large investments in production capacities of well over 4 trillion € until 2050. However, with expected future production cost for sustainable aviation fuels of 1-2 €/L, an economically competitive production of sustainable aviation fuels can be achievable in the next decades. The results show one possible pathway to get close to the ATAG goal for 2050 with different alternative fuel options while considering their theoretical feedstock potential from waste streams.

Abbrevations

ACI	*Airport Council International*	*IATA*	*International Air Transport Association*
AF	*Alternative Fuel(s)*	*ICAO*	*International Civil Aviation Organisation*
APU	*Auxiliary Power Unit*	*LNG*	*Liquified Natural Gas*
ATAG	*Air Transport Action Group*	*MFSP*	*Minimum Fuel Selling Price*
ATM	*Air traffic management*	*NASA*	*National Aeronautics and Space Agency*
CO_2	*Carbon dioxide*	*PtL*	*Power-to-Liquid*
CORSIA	*Carbon Offsetting and Reduction Scheme for International Aviation*	*RPK*	*Revenue Passenger Kilometre*
DAC	*Direct Air Capture*	*TCT*	*Thermochemical Conversion Technologies*
EIS	*Entry Into Service*	*TRL*	*Technology Readiness Level*
FT	*Fischer Tropsch*	*SAF*	*Sustainable Aviation Fuel*
GHG	*Green House Gas*	*SRIA*	*Strategic Research and Innovation Agenda*
HEFA	*Hydroprocessed Esters and Fatty Acids*	*UCO*	*Used cooking oil*

I. Economic and technological long-term developments in aviation

In the last years, radical aviation technologies like hybrid-to-full electric or hydrogen as energy source for the propulsion system have been investigated[1,2,3]. These technologies might deliver emission and global warming reduction potentials, however a large impact on aviation stakeholders is expected. Especially aircraft and engine manufacturer have to mature these technologies to be able to deliver competitive designs, industrial manufacturing processes and supply chains as well as high operational reliability. For airports worldwide, these novel energy sources might require additional infrastructure for energy supply, storage and distribution. Therefore, large investments would be expected for these radical aviation technologies. Together with long timeframes for the market uptake of these technologies, the question arises, if drop-in alternative fuels might not be a more cost-competitive solution for aviation in the long-term. In this paper, possible pathways to fulfil long-term emission reduction goals in aviation towards the year 2050 will be proposed assuming an evolutionary aircraft technology development approach where conventional tube-in-wing aircraft configurations as well as drop-in fuels as energy source will found the basis for the analysis. Based on long-term emission reduction goals for aviation towards the year 2050, these pathways based on previous published, future air transport growth scenarios[47] coupled in this paper with possible aircraft technological improvements, requiring evolutionary changes to the existing aviation system with its stakeholders.

To fulfil these long-term emission goals, emission gaps will be compensated by alternative fuel options and potential ramp-up scenarios will be developed. Finally, this paper concludes with required alternative fuel quantities, required production ramp-up as well as possible investment and production costs for these alternative fuels.

A. Long-term aviation market forecasts

Aviation transformed from an elite mode of transport for niche markets to a mass transportation system serving long-haul as well as medium and short-haul markets worldwide since the last 100 years. Over the past decades, the aviation industry has grown strongly - measured in transport capacity (revenue passenger kilometres, RPK)- at a global rate of around 5 % per year[1] and above. All main aviation stakeholders[4-14] predict further growth in transport capacity until 2030-2040 timeframe at global average. IATA[4] forecasted an average growth of 3.9% per year up to 2036. Airbus[5] instead forecasted an annual growth rate of 4.9% up to the year 2026 and 4.1% from 2027 to 2036. Airport Council International[6] (ACI) as well as ICAO[11] forecasted an average annual growth of 4.5% up to the year 2040 (ICAO). Particularly high growth rates, partly surpassing 6 % per year, are expected for emerging countries, for example in the Asia-Pacific region, driven by the transition to middle- or even high-income countries with a growing middle class and the associated changes in travel behaviour[15].

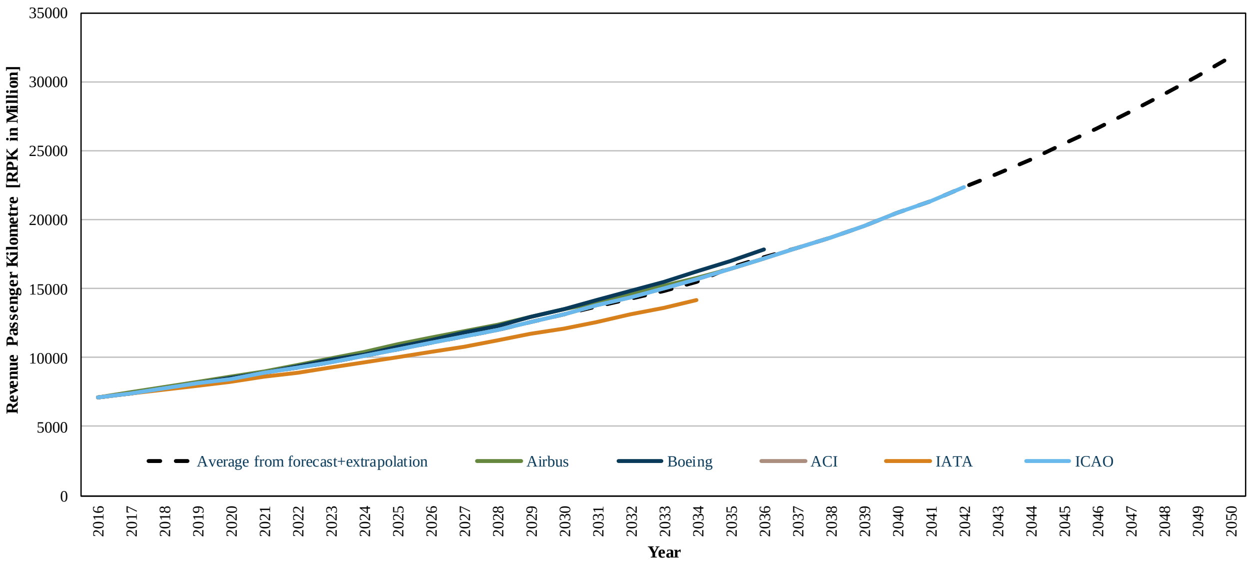

Figure 1: Summary of five different aviation forecast up to the year 2040, average growth function as well as extrapolation up to the year 2050.

In order to derive air traffic growth rates for a future reference scenario, industry growth data forecasts from ICAO[11] were used up to the year 2040 and extrapolated to the year 2050 as shown in figure 1 above. This growth roughly translates into a doubling of transport capacity by 2030-2035 timeframe and quadrupling capacity in the 2040-2050 timeframe compared to today.

B. Long-term environmental goals for aviation

Within the context of this rapid growth of aviation, environmental awareness of societies and general actions to mitigate global climate change have led various institutions and stakeholders to formulate and proclaim aspirational, partially non-binding quantitative goals for limiting greenhouse gas emissions (GHG) of the future global air transport fleet. Among these institutions are the International Civil Aviation Organization (ICAO)[16], the International Air Transport Association (IATA)[17], the Air Transport Action Group (ATAG)[18] and the European Union (EU)[19]. The most prominent and frequently cited targets addressing the emission quantities of carbon dioxide (CO_2) at global aircraft fleet level have been published by IATA and ATAG and comprise three major items:

(1) Fleet-wide efficiency improvement of 1.5 % annually from the present until 2020
(2) Cap of CO_2 emissions from 2020 onwards ("carbon-neutral growth") enabled by market-based measures
(3) Halving of the global fleet's overall net emissions by 2050 relative to 2005 levels

At aircraft level, the EU envisages in its long-term research agenda[19], a reduction of CO_2 emissions by 75 % compared to typical aircraft in service in the reference year 2000. The EU targets are considered as being on an equal footing with those announced by ICAO, IATA, and the U.S. National Aeronautics and Space Administration (NASA)[20], levelling the long-term research goals for aircraft technologies. Technology goals for CO_2 emissions, as originally defined in Vision 2020[21] and AGAPE 2020[22], were categorised into airframe, propulsion and other areas like air traffic management (ATM) and airline operations. Up to the year 2035, a 60 % reduction in fuel burn and CO_2 emissions per RPK is to be achieved, and a 75 % reduction in CO_2 emissions is set as a target for the year 2050, relative to technology standards of the reference year 2000.
Considering the Paris Agreement – which aims to limit global temperature increase to 1.5°C – a reduction of aviation CO_2 emissions appears even more necessary and challenging beyond 2050 timeframe. If all sectors of the economy take ambitious actions, aviation could be responsible for 22% of global emissions[23] in 2050. It is thus unlikely that aviation would comply with the Paris Agreement with the current emissions reduction goals – which are already challenging.

C. Short-to-medium term developments in aviation

Besides these long-term research goals to reduce the ecological footprint at aircraft level, aircraft manufacturers are continuously updating their current product portfolio with completely new aircraft programmes and performance improvement packages for existing product lines. A strong focus, and hence competition was set over the last 10 to 15 years on new long-haul aircraft programmes, like Airbus A380, Boeing 787, Boeing 747-8, and Airbus A350, which entered the markets in 2005, 2011, 2012 and 2014, respectively. The Boeing 787 achieved a block fuel reduction compared to its predecessor – the Boeing 767 – of around 20 %.[24]. A 25 % block fuel reduction is claimed for the Airbus A350, compared to the current Boeing 777 family[25].

Besides new aircraft programmes, both Airbus and Boeing will also improve their existing A330 and 777 programmes by more efficient wing designs and incorporating latest available engine technologies, resulting in the Airbus A330neo (new engine option) and Boeing 777-8/9 family, achieving block fuel reductions between 13% and 20 %.

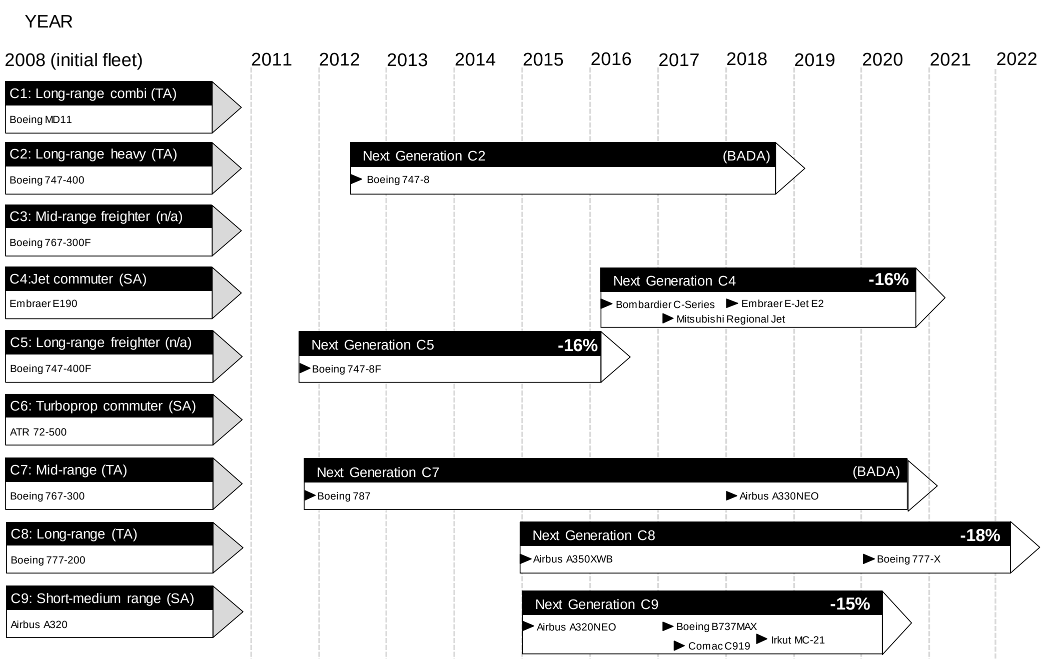

Figure 2: Next-generation aircraft types and associated gains in fuel efficiency[26] launched until 2017

For the short-haul markets, the availability of the Geared Turbofan engine technology, offering promising fuel burn reductions of around 15 %[27], led to several launches of new programmes like Bombardier's CSeries or existing aircraft programmes like Airbus' A320 and Boeing's 737 families being updated with this latest engine technology.

However, despite these substantial efforts to develop new or upgraded aircraft programmes in order to increase fuel efficiency, it is obvious that the target of carbon-neutral growth from 2020 onwards will not be met. Today, more than 14,000 single-aisle aircraft are operating, and a growth to over 30,000 aircraft within the next 20 years is expected[28]. Even at current highest production rates of around 120 aircraft per month for Airbus A320 and Boeing 737 single-aisle aircraft families, the limited rate of market penetration of new and more efficient aircraft is slowing down the overall ambitious emission reduction targets on fleet level.

II. Technological, operational and alternative fuel options for aviation

A. Selected technological and operational options for aviation

The aviation research community investigates a large array of possible future aircraft technologies to further improve aerodynamic, structural, system and propulsion efficiency. Some of these technologies have significant impact on various aviation stakeholders like aircraft manufacturer, aircraft operators or airports. Especially non-drop-in fuels like hydrogen and partly (hybrid-)electric propulsion systems require significant changes to aircraft design, production, operation and servicing on ground.

Aerodynamic efficiency improvements are realised e.g. by high aspect ratio or strut-braced wings, foldable wing tips being applied beyond the Boeing 777-8/9, (hybrid) laminar flow or even blended-wing-body configuration are under investigation[1]. For the aircraft structure, novel light weight materials, composites together with nature-inspired design enabled by additive layer manufacturing promise further weight reduction.

Besides improving aerodynamics and reducing structural weight of the airframe, also efficiency improvements of the aircraft systems are targeted. Promising developments are fuel cell based auxiliary power unit (APU) together with a more to all electric system architecture.

To further increase the propulsion efficiency, manufacturer look at novel ways to increase overall pressure ratio and temperature levels by new materials, second generation of geared turbofan being also applied at larger engines with higher thrust levels, novel thermodynamic cycles like composite cycle engines[29] or even open rotor concept[1].

As the focus in this paper is set on a more evolutionary approach for novel aircraft and engine technologies, only tube-in-wing configurations and drop-in fuels will be investigated. Radical novel aircraft technologies like blended-wing-body configuration, distributed propulsion with a strongly coupled airframe, propulsion system integration are not considered in this paper. Additionally, novel energy carrier technologies like hydrogen, liquid natural gas (LNG) or hybrid-electric aircraft requiring battery and energy supply on the ground are also not considered in this study.

IATA concluded together with the German Aerospace Centre (DLR) in their Technology Report 2013[1] that new aircraft designs after 2020 with (hybrid) laminar flow and fuel cell APU application might result in -27% fuel burn reduction in case of short range A/C to -40% fuel burn reduction in case for a long-range aircraft. With serial upgrade of the current aircraft programmes, they concluded that fuel burn reductions of -9% up to -20% can be achieved[1].

Based on studies from Heinemann et al.[30] looking at potential fuel burn reduction in the timeframe 2050 for a tube-in-wing configuration, possible fuel burn reduction up to 60% for a short-range, tube-in wing open rotor configuration and 47% fuel burn reduction for an A330 type long-range aircraft were estimated. Both configurations will fall short by 20% (short-haul) and 37% (long-haul) relative to the set target. Isikveren et al. estimated in their study that more evolutionary technologies for tube-in-wing configuration will results in a 15-20% shortfall compared to 2035 and 2050 fuel burn reduction targets[31].

All investigated studies show a significant fuel burn reduction potential compared to year 2000 reference technology, however shortfalls compared to the SRIA 2035 and Flightpath 2050 goals of 43% and 75% respectively can be observed. Therefore, in this paper a conservative technology development and application scenario is taken into account, assuming that no new aircraft program (e.g. Airbus A320 or Boeing 737 successor) will be launched until 2035. Only additional wing and engine upgrades are assumed leading to an average fuel burn reduction of -22% compared to 2000 reference technology. Furthermore, with the evolutionary technology maturation approach in this paper, it is assumed that new aircraft programs launched in the timeframe between 2035 and 2050 will still show shortfalls in targeted fuel burn by 20%.

B. Selected alternative fuel options for aviation

In addition to technological and operational measures, alternative energy carriers represent an important option for reducing GHG emissions of aviation[32,33]. In this paper, the analysis is confined to sustainable *drop-in* fuels (in the following simply termed sustainable aviation fuels, SAF) for three reasons. First, current aircraft could be fueled by SAF without any technical adaptation, thus considerably reducing the cost associated with large-scale uptake of SAF on a systemic level. Second, SAF hold the potential to completely substitute fossil fuels, as sufficient renewable primary energy sources exist and will likely be accessible in the mid to long term. Third, the technologies to produce SAF are partly already available. Thus, SAF could in principle substitute significant amounts of fossil fuel within a few years.

However, the current production capacities of alternative fuels are rather limited. The positive examples of alternative fuels consumption mainly comprise demonstration flights and small-scale projects of several airlines[a]. Thus, a faster ramp-up of production capacity will be necessary in order to achieve a substantial share of SAF in the overall jet fuel mix within the next years. At present, however, higher investment rates seem unlikely, as production cost of SAF are high and fossil oil prices relatively low. The question thus is to what extent and by when alternative fuels can substitute fossil fuels, at which future prices, and with which environmental benefit. In addition to the issue of limited production capacities, the sustainable availability of feedstock can fundamentally limit the production potential. This is particularly true for production pathways that depend on biomass feedstock where utilization often raises concerns regarding sustainability.

Alternative drop-in fuels can be produced from a wide variety of feedstocks and energy sources and through different conversion and refining technologies. Comprehensive reviews of the various production pathways currently under development can be found in the scientific literature, e.g. by de Jong et al.[34] or from the EU-funded project CORE-JetFuel[35]. The current technology landscape for alternative drop-in fuels is both promising and inconclusive. On the one hand, some pathways have already reached high maturity levels, but are relatively limited in terms of feedstock availability. On the other hand, newly developed technologies have the potential to completely substitute fossil fuels, but are currently years – if not decades – away from industrial deployment. In the following, we focus on three prominent, but very different families of conversion technologies (see also Table 1): Hydroprocessing of oils and fats (HEFA), thermochemical conversion of biogenic (mainly lignocellulosic) feedstock, and Power-to-Liquid. The analysis generally confines to wastes and residues as biomass feedstock in order to minimize the risk of unsustainable production of dedicated energy crops[b].

HEFA currently represents the only production process for renewable jet fuel that is industrially implemented at substantial scale, and consequently HEFA-SPK is the only renewable jet fuel commercially available in relevant quantities at the moment. Still, the demand for HEFA fuels remains low, with announced off-take agreements not surpassing 1 Mt for the next five years and commitments remaining vague[c]. Nonetheless, HEFA will most probably remain the only viable technology to produce alternative drop-in fuels for the next 5-10 years at substantial scale. This poses the question, how much HEFA fuel can potentially be produced from waste oils and fats. Consistent figures of the global potential of used cooking oil (UCO) as most prominent oleaginous waste do not exist. Spöttle et al.[36] estimate the potential of UCO for the EU, the US, China, Argentina and Indonesia at around 2 Mt per year, but acknowledge that the uncertainty for this figure is high. However, it is likely that the global theoretical potential of UCO is limited to 5-10 Mt per year. Taking into account a mass-based conversion rate of 0.6 from UCO to kerosene, a maximum of 6 Mt of fuel could be provided from the 10 Mt UCO feedstock.[53].

Thermochemical conversion technologies (TCT) cover a wide variety of biomass feedstock and production technologies. In this paper, a short description of the process of gasification of biomass followed by Fischer-Tropsch (FT) synthesis as the most advanced of several TCT[d] is provided. Essentially, this conversion technology comprises three basic steps: (i) thermal gasification of feedstock to generate syngas (a mixture of hydrogen and carbon monoxide), (ii) conversion of syngas into hydrocarbons through FT synthesis, and (iii) refining of the crude FT product (FT crude) into final fuel products, e.g. jet fuel. Recently, several industrial commercialization projects, most prominently by the US-based companies Red Rock Biofuels and Fulcrum Bioenergy, have been announced. Completion of these projects would raise the technology readiness level of this production pathway to industrial maturity. In terms of sustainable feedstock, TCT can draw on essentially any dry carbonaceous material, including energy crops and biomass wastes and residues. For reasons of sustainability and simplicity, the present analysis is limited to wastes and residues from both agriculture and forestry. Here, the feedstock potential is substantially larger than in case of HEFA, with roughly 85 Mt per year from agriculture and 9 Mt per year from forestry for Europe[37].

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[a] A current overview can be found under: https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx

[b] Certainly, other sustainable feedstock beside waste and residue streams exist, but for the scope of this paper, a stricter selection of analyzed feedstock seems more adequate.

[c] See https://www.icao.int/environmental-protection/GFAAF/Pages/Facts-Figures.aspx

[d] Besides gasification, hydrothermal liquefication and pyrolysis are two other prominent conversion technologies. Here, we focus on gasification as it is the process closest to commercialization.

Applying a conservative extrapolation, the global potential of forestry and agricultural residues would likely surpass 400 Mt per year. These 400 Mt of biomass can be transformed to roughly 80Mt of fuel[38].

Table 1: Key figures for the selected three families of SAF production technologies

	HEFA	**TCT**	**PtL**
Feedstock type	Oils and fats (here: UCO)	Any dry biomass material (here: agricultural and forestry residues)	Renewable electricity, CO_2, water
TRL[35]	9	4-6	4
Theoretical feedstock potential for SAF production	10 Mt (UCO) [36]	400 Mt (agricultural and forestry residues, dry mass) [37]	Essentially unlimited[a]
Theoretical fuel potential	6 Mt (from UCO)	80 Mt (from agricultural and forestry residues)	Essentially unlimited
Specific GHG emission reduction [b]	-69% [35]	-85 to -95% [35]	-96% [35]
Highest uncertainty	Limited feedstock potential (e.g. due to competition from other sectors)	Feedstock prices; sustainable feedstock potentials	Low current technological maturity and cost of DAC; cost of renewable electricity generation

Finally, the **Power-to-Liquid (PtL) pathway** represents another promising option. The PtL pathway is driven by (renewable) electric energy and does not rely on biomass as feedstock. The only required feedstocks are water (as hydrogen source) and carbon dioxide (as carbon source). In a first step, electrical energy is applied to split water into hydrogen and oxygen. In a second step, the generated hydrogen is used to reduce CO_2 to carbon monoxide (CO) which is mixed with more hydrogen to form syngas. In a third step the syngas is converted to liquid hydrocarbons through FT synthesis. PtL technologies have the potential to produce carbon-neutral fuels, provided that the applied electric energy as well as the feedstock water and CO_2 are generated from renewable sources. To make use of the vast scalability of PtL production, it is generally expected that the required CO_2 will have to be provided from direct air capture (DAC), rendering DAC a key technology for large-scale roll-out of the PtL production pathway. Further, PtL technologies have the advantage that their production potential essentially has no upper boundary, as renewable electricity generated from solar energy is a quasi unlimited energy sources and CO_2 (from DAC) as well as water (e.g. from sea water desalination) can be provided in a truly renewable way. However, production of liquid hydrocarbon fuels via PtL is not yet industrially mature and considered a technology option for medium-term future application.

In summary, it is thus reasonable to assume that overall the theoretical production potentials do not pose a substantial limiting factor for the substitution of fossil kerosene by renewable alternatives in the long term. However, with respect to individual production pathways, the question of when and to what extent a certain production technology will be realized depends on the availability of the specific feedstock, the maturity of the specific conversion technology and, most importantly, the specific cost of fuel production. These issues will be further discussed in section IV.

III. Technological and operational scenarios on aircraft fleet-level

To be able to quantify the effectiveness of various technological and operational improvement on global emissions in 2050 as well as cumulative global emission up to the year 2050, a baseline scenario was defined taking aircraft technologies and configurations, aircraft production ramp-ups, aircraft productivities, RPK growth changes and retrofit options similar to Dray et al.[41] into account.

For this study, the baseline scenario[42] is based on the assumption that the aviation industry can not develop and deliver new aircraft following the SRIA goals of -43% fuel burn reduction of all new aircraft with Entry-Into-Service

[a] Considering the vast potential of renewable electricity generation, provision of CO_2 through direct air capture and of water from sustainable sources, e.g. from sea water desalination.

[b] Relative to conventional jet fuel. The specific GHG emission reduction is calculated from the difference between the specific lifecycle GHG emissions of the alternative jet fuel under investigation x_{SAF} and of conventional jet fuel x_{cjf}, according to: $(x_{SAF} - x_{cjf}) / x_{cjf}$.

(EIS) between 2020 and 2035, -60% fuel burn with EIS between 2035 and 2050. Instead, only a -22% fuel burn reduction (~50% shortfall due to no new A/C programs) for aircraft between 2020 and 2035 are assumed taking into account that most of the current aircraft programs will be upgraded by re-engined, re-winged options[43]. Between 2035 and 2050, it is assumed that aviation industry still shortfalls in block fuel reductions on aircraft level until 2050 as no radical new aircraft technologies like novel airframe morphologies or non-drop-in energy carriers were considered.

Market uptake and penetration effects of new aircraft technologies are captured by current industry standard of six years from first delivery to full-production rate. Until 2020 production rates and production increases of current aircraft programs following an analysis of Leeham[44], after 2020 it is assumed that aircraft production increases with RPK growth. Besides the aircraft technologies and production capabilities, possible emission reduction options on an operational level e.g. by cabin densification and load factor increase were also not considered. A gradual 10% fuel burn reduction was taken into account from 2020 to 2030 accounting for improvements in air traffic management[45].

Table 2. Summary of considered technological and operational cases

Category	Input for Fleet Simulation Framework
Aircraft technologies & configurations	2020-2035:-22% (~50% shortfall due to no new A/C programs) fuel burn of re-engined, re-winged A/C 2036-2050: -48% (~20% shortfall) fuel burn of all new aircraft with EIS between 2035 and 2050
Aircraft production ramp-up	Aircraft production up to year 2020[44], linear upscale with RPK growth New aircraft programs with current ramp-up timelines of six years (status quo)
Operations	No increase in average loadfactor, no additional cabin densification -10% fuel burn reduction enabled by improved air traffic management
RPK growth	Average +4.5% world wide from 2008 to 2050

IV. Air transport fleet modelling

Given the goals of this paper, a simplistic comparison of the performance of current and next-generation aircraft types at a single-mission level is insufficient. Instead, fleet-wide effects resulting from the phase in and decommissioning processes of aircraft types that enter the global fleet at a certain moment in the future have to be taken into account. Once a new type has reached technological maturity for commercial operations with an airline, it will not simply replace all of the corresponding older types at once but gradually replace these aircraft and, in this way, replenish the airline's fleet. In order to capture the integration and penetration effects of the next-generation aircraft and technologies, the "Fleet System Dynamics Model (FSDM)" has been developed and further extended[26,46,47].

The FSDM models both the global air transport network as well as the global aircraft fleet in order to evaluate the fleet-wide effects. Fleet-wide effects not captured in the assessment of a single aircraft type include both aircraft commissioning and retirement processes as well as dynamic aircraft type allocation in the global air transport network. The fundamental principles of the FSDM are derived from the "macro" or "top-down" approach to fleet planning translating air traffic growth rates addressing the future aircraft fleet[48].

The fundamental philosophy underlying the entire aircraft technology assessment technique at a fleet level basis is one that integrates scenario planning techniques. This considers the element of uncertainty in the assessment with prolonged time horizons. Specifically the FSDM relies on quantitative scenario-based data derived from an intuitive qualitative scenario planning approach on a global level[46]. This core underlying philosophy of integrating scenario planning techniques to deal with the issue of uncertainty differentiates our air transport fleet modelling approach from an approach based on parametrical assumptions to determine boundary conditions of the system model[49].

The FSDM is divided into two model components: the aircraft fleet model and the air transport network model. The aircraft fleet model calculates the size and structure of the global aircraft fleet on a yearly basis. The time-step used in the model is one year. For each simulation year, the model reads the annual growth rates of the Available Seat Kilometres (ASKs) and Available Tonne Kilometres (ATKs) as well as load factor data determined using a scenario-based approach. This determines the "capacity gap", that is the demand for new aircraft units to fulfil the overall annual air traffic growth rates in order to deliver the requested transport performance.

Initialisation of the model is required that includes the definition of the start year and initial fleet and as mentioned in the first paragraph above, using scenario-based quantitative data for the appropriate scenario.

The most important model assumptions used in the FSDM include the categories of airline competition, fleet allocation, global aircraft fleet modelling and route network.
Explicit modelling of airline competition is excluded from the FSDM. The overall network system and aircraft fleet development reflects “one benevolent, monopolistic airline”, a termed coined in the work of Tetzloff and Crossley[50]. The “Fleet Assignment Problem” implemented in the FSDM assumes a fuel burn optimization function minimising the total fleet fuel consumption instead of a profit maximization function[46].
Representing the global air transport fleet to reduce modelling complexity are nine distinct aircraft categories of the global fleet in 2008. Additional new aircraft can be added and simulated in the model for technology evaluation at the aircraft level. Similar to the global air transport fleet, the global route network is defined by twenty-one intra- and interregional connections between six global regions (Africa, Asia, Europe, Latin America, North America, and the Middle East). Data from the OAG database in 2008 were analysed statistically to define the various relevant stage lengths for the global aircraft fleet[46]. The model includes statistical parameters like the aircraft utilization, load factor, retirement functions and other changes in aircraft supply and decommissioning. For simplicity, these parameters were set constant in this study. Temporary storages of aircraft in a market faced with oversupply are not included in the FSDM[46].

V. Evolutionary technological, operational and alternative fuel scenarios

As shown in Figure 3, the introduction of new aircraft programs with lower fuel burn (-22 % in 2020-2035 and -48% in the timeframe 2035-2050) show a significant reduction on fleet level fuel burn for the *Baseline* Scenario scenario compared to the *No Action* scenario after 2035. In the *No Action* scenario, fleet-level fuel consumption rises from 183Mt to 272Mt in 2020, 436Mt in 2035 and 831Mt in 2050. The *Baseline+ATM* scenario, a fleet-level fuel burn reduction of 1% in 2020, 20% in 2035 and 46% in 2050 can be achieved following the evolutionary aircraft technology approach. Comparing the *Baseline+ATM* scenario with the ATAG goals, a short fall between calculated fleet-level fuel burn and target fuel burn can be observed. Between 2008 and 2020, this gap growths from 5% in 2008 to roughly 20% in 2020, mainly due to strong aviation market growth outpacing continuous efficiency improvements from latest aircraft programmes. After 2020, the aviation industry will offset their additional carbon dioxide emissions by the global CORSIA. In case of the *Baseline+ATM* scenario and neglecting higher emissions between 2005 and 2020 compared to the ATAG 2005 reference scenario, the aviation industry has to offset 124MT of fuel burn in 2035 which accounts to roughly 35% of the overall fuel burn.

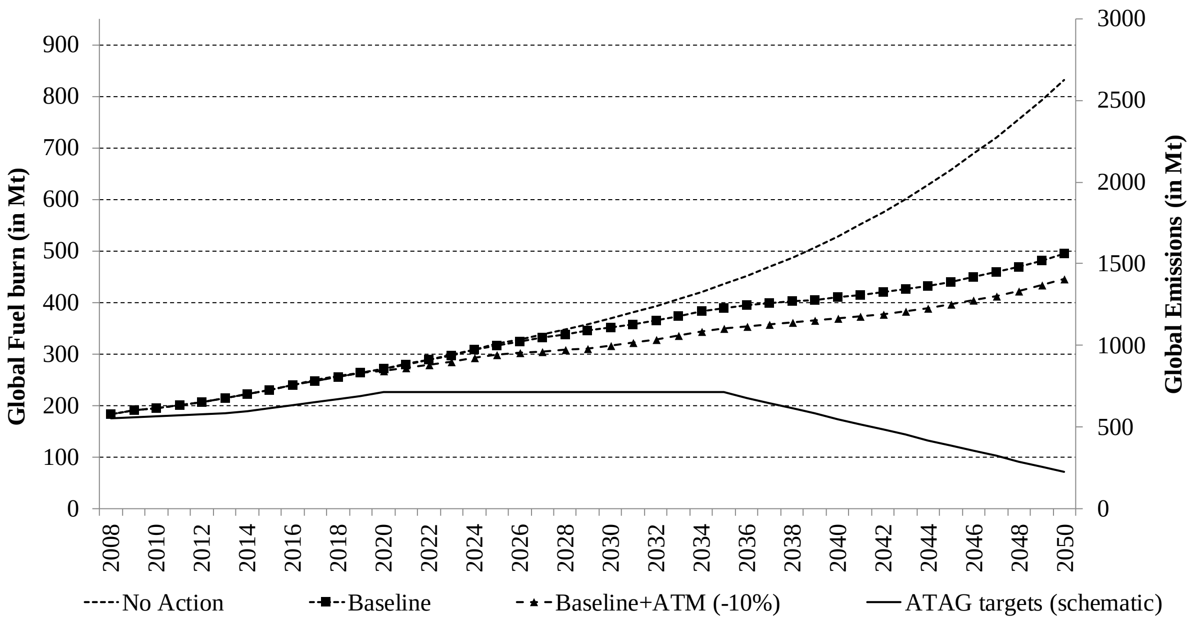

Figure 3: Global fuel burn for aviation from 2008 to 2050 for No Action, Baseline and Baseline+ATM scenario compared to the ATAG goals.

A. Alternative fuel production ramp-up scenarios

Even with substantial improvements in fuel efficiency, SAF will have to substitute a large share of fossil jet fuel in order to achieve the ATAG goals of -50% net emissions relative to 2005 level. Based on the scenarios described above (see figure 3), the expected difference in fuel burn between the *Baseline+ATM* scenario and the ATAG targets amounts to roughly 124 Mt in 2035, and more than 375 Mt in 2050. Thus, in order to close this gap, at least 124 Mt of SAF per year will have to be produced after CORSIA is scheduled to end in 2035, and 375 Mt per year will have to be provided by 2050. When assuming that SAF will not be 100% emissions-neutral (no net emissions), these figures will be even higher. This requires huge investments in the expansion of alternative jet fuel production capacities, which cannot be achieved overnight. A high-level picture of the dimension of needed production capacity developments was presented by Koops & Sizmann[54]. In order to better understand the development of the mix of fuel production technologies and their relative impact, a simple scenario is constructed. First, it is assumed that production capacity dynamics follow an S-shape, with relatively low build-up rates in the first years of commercialization, feedback effects during the high growth periods, and reduced build-up rates once feedstock or demand limits are approached[55].

Further, we take into consideration the differences between technology families with respect to technological maturity and maximum production potentials to estimate when production capacities are built up, and how much fuel can be produced. HEFA fuels are already commercially available, but waste feedstock are – with a maximum global potential of about 10 Mt per year – rather limited. Thus, HEFA will likely be the only industrially available technology for alternative fuel production in the next five to ten years, but feedstock availability will relatively quickly become an issue. Consequently, thermochemical technologies capable of converting lignocellulosic feedstock would become suitable complementary pathways to HEFA between 2025 and 2030, once the demand for HEFA feedstock approaches the supply potentials. Once commercialization of gasification/FT technologies is achieved, the large feedstock potential of around 80 Mt of fuel per year would make it possible to produce large fuel quantities on a sustainable basis. Yet, the theoretical potential of agricultural and forestry wastes and residues would also not suffice to substitute enough aviation fuel to reach the -50% CO_2 emissions goal. Therefore, PtL technologies are assumed to become industrially available at large scale, with the first industrial plants entering into service at around 2023. Once commercialized at full scale, unrestricted technical scalability can be expected for the PtL pathway, as the supply potential of renewable primary energy is essentially unlimited. Growth rates for PtL capacity are thus only restricted by economic framework conditions, most notably, market demand.

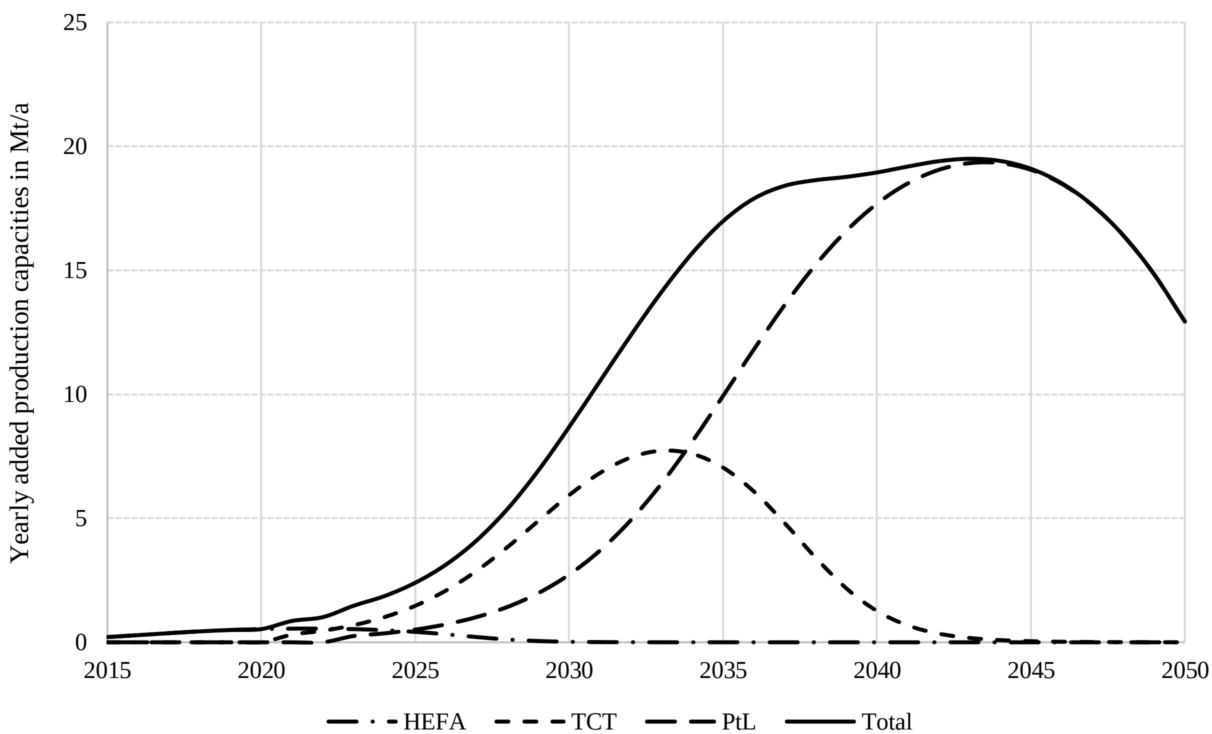

Figure 4: Estimation of the required expansion of new fuel production capacities for different SAF technologies for the period 2015-2050

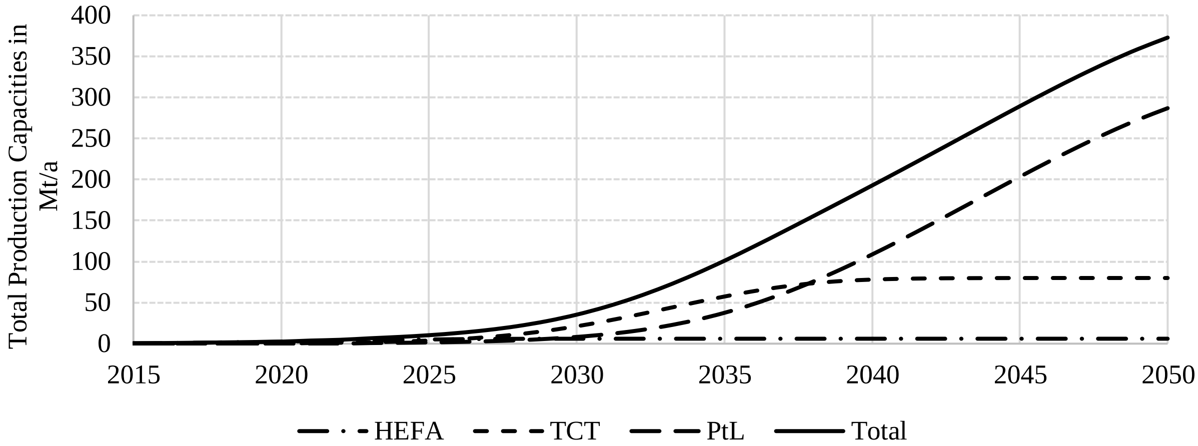

Figure 5: Estimation of the required cumulative fuel production capacity for different SAF technologies for the period 2015-2050

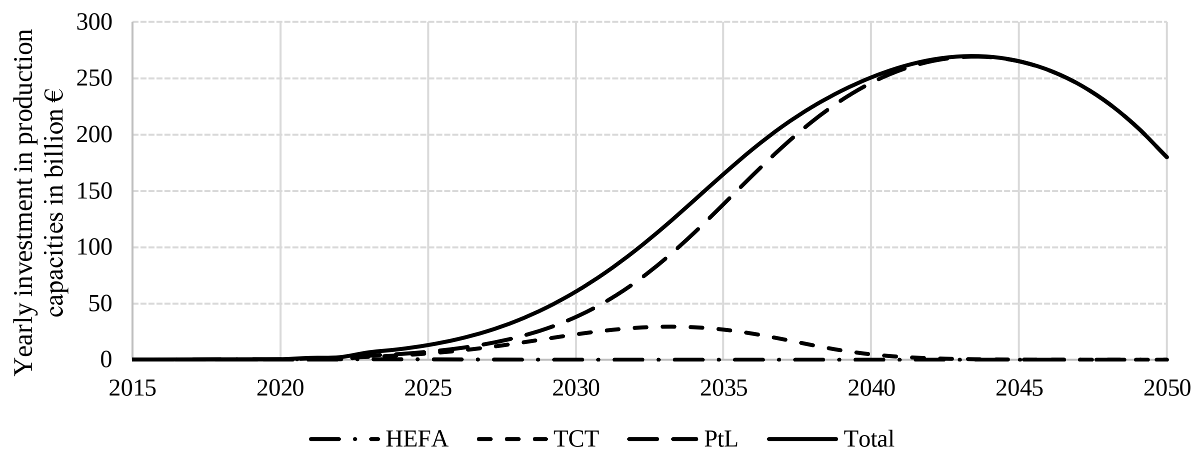

Figure 6: Annual required investment for expansion of fuel production capacity for different SAF technologies in the period 2015-2050

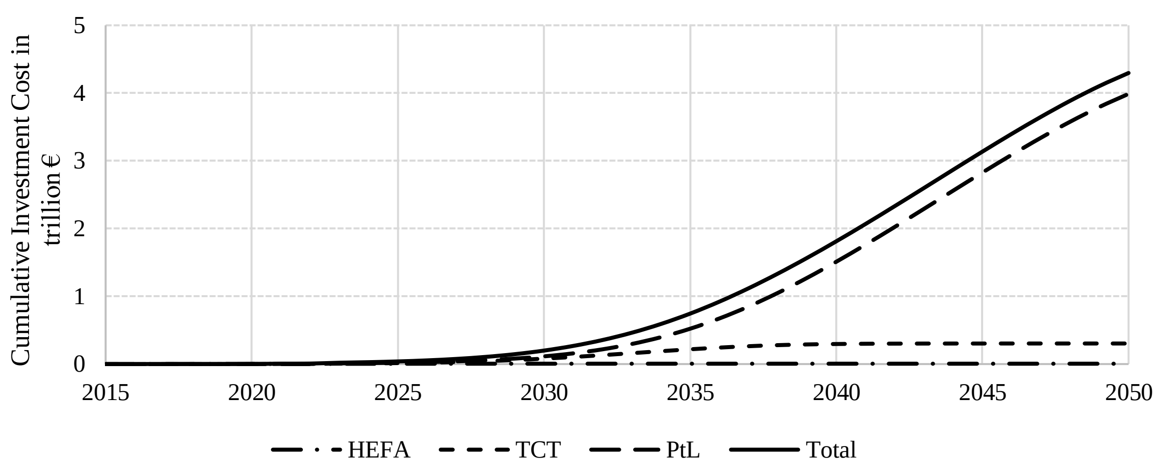

Figure 7: Cumulative investment corresponding to the required expansion of fuel production capacity for different SAF technologies in the period 2015-2050

Under these assumptions, achieving the ATAG goals would require a strong increase in renewable fuel production capacity, as shown in Figure 4 for the high-level scenario assumed here. The strongest efforts would thus be needed during the period 2030-2045, with a yearly growth in absolute production capacity of 10 to 20 Mt. However, it is important to emphasize that the period until 2030 is equally crucial in order to develop SAF technologies to a level of maturity that allows a rapid large-scale roll-out in the following years. If the aviation industry, fuel producers and policy do not increase their efforts to push SAF towards commercialization and large-scale production in the next decade, it will be very challenging to achieve the rapid ramp-up of production required in the period 2035-2050.

With respect to the economic viability of SAF, costs of production in the order of 1-2 €/L can be expected for mature full-scale production facilities, depending on feedstock, technology and other input price assumptions. For optimistic scenarios, Minimum Fuel Selling Prices (MFSP) are expected to be at 1.01 €/L for HEFA (UCO)[34], 1.33/1.93 €/L for TCT (Gasification with forestry residues/wheat straw)[34], and 0.88 to 1.45 €/L for PtL[39, 40]. In this context, it is important to note that the assessment of costs of production of SAF is associated with high uncertainties. Many techno-economic assessment studies have been published to date with often significantly varying results. This is a consequence of different chosen boundary conditions, accounting methodologies and technical and economic assumptions underlying the respective assessment. The above-cited values therefore represent a non-exclusive and non-exhaustive selection. Nevertheless, it presented values give a good indication of the economic obstacle in the way of large-scale implementation of SAF, if compared to today's average market price of conventional jet fuel of about 540 €/t or 0.43 €/L[52]. It is difficult, if not impossible, to predict if and when cost-competitive production of truly sustainable jet fuel at large scale will become possible, as this depends not only on the future development of production cost, but also on the development of the market price of conventional jet fuel. Conceivable reasons for increasing fossil fuel prices are the rising mobility and overall energy demand and ultimately limited crude oil resources. In contrast, large-scale implementation of electro mobility or deployment of unconventional fuels, such as hydrogen or methane, could reduce the demand for and prices of crude oil-derived fuels. Yet, even if an economically competitive production of SAF can be achievable in the next decades, a formidable challenge lies in the high investment costs associated with the construction of the required production plants with sufficient capacities. In order to draw a rough picture of investment costs required to build up sufficient production capacities to meet that ATAG target for 2050, a simple investment cost estimation can be conducted based on the following assumptions. It is assumed that HEFA facilities can be realized at investment costs of 0.87 M€ per kt/a production capacity[34], TCT plants at 3.8 M€ per kt/a, and PtL facilities at 13.9 M€ per kt/a. Note that PtL investment cost include electricity generation by wind power and CO_2 provision by Direct Air Capture. These two measures make up around 80% of the total investment cost for PtL. Thus, setting up capacities to produce around 375 Mt of SAF per year (see Figure 5) would require investments of roughly 4.3 trillion € between 2015 and 2050 (figures 6 and 7). This, indeed, is an impressive amount of investment capital, resulting from the fact that production of SAF is generally capital-intensive, particularly in case of PtL. However, it has to be kept in mind that the operating cost of PtL are comparably small, resulting in overall cost of production that are comparable to other SAF options and that can even favorable compared to other alternatives under optimistic conditions.

VI. Conclusion and Outlook

Simulating the impact of new aircraft programs applying more evolutionary technologies with shortfalls of 20% to 50% compared to Flightpath 2050 goals lead to a reduction of the fleet-level fuel burn by 1% in 2020, 20% in 2035 and 46% in 2050. Yet, comparing these results with the ATAG goal, the aviation industry has to offset emissions from around 124 Mt of fuel burn in 2035 accounting for roughly 25% of the overall fuel burn. From 2020 and beyond, a large amount of sustainable alternative fuel (SAF) with low CO_2 footprint are required leading to large investments to increase the production capacity.

With regard to sustainable alternative fuels, it is highlighted that they have the potential to completely substitute fossil fuels. However, this requires substantial investments in production capacities. A basic scenario for the development of SAF production capacities showed that substantial efforts have to be taken by the aviation industry stakeholders, especially during the years 2030-2045. If indeed 375 Mt of fuel per year would be substituted by SAF by 2050, roughly 4.30 trillion € of investment in additional production capacities would be needed over a period of 35 years. It is important to note that the presented scenario is purely hypothetical and ignores a range of obstacles and uncertainties. Also, for the sake of simplicity, we assumed that all provided SAF are produced carbon neural, which is not the case in reality. Thus the actual amount of SAF needed to achieve the ATAG goals would be somewhat higher. Yet, the aim of this scenario exercise is not to give the most probable future development, but to show one possible pathway to get close to the ATAG goals with different alternative fuel options. When considering their theoretical feedstock potential from waste streams and the expected investment cost, it becomes clear that the economically favorable HEFA and TCT pathways can only represent a small share of total future production. Rather, substantial investments in expensive, but highly scalable pathways like PtL will be necessary. Further research is needed to better understand feedstock availability and technological progress for alternative drop-in fuel technologies for the next decades to come, and to formulate sounder future scenarios. Then, more fine-grained recommendations can be given with respect to the sustainable development of the aviation sector.

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