33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

SUSTAINABLE AVIATION FOR SWEDEN - TECHNOLOGY & CAPABILITY ASSESSMENT TARGETING 2045

Christopher Jouannet[1], Ingo Staack[2], Tomas Grönstedt[3], Xin Zhao[4], Petter Krus[5], Anders Lundbladh[6], Björn Nagel[7]

[1]Principal Engineer Advanced Design, Saab Aeronautics, Linköping Sweden
[2]Senior Lecturer, Linköpings University, Department of Management and Engineering, Linköping Sweden
[3]Professor, Mechanics and Maritime Sciences, Division of Fluid Dynamics, Chalmers, Gothenburg, Sweden
[4]Researcher, Mechanics and Maritime Sciences, Division of Fluid Dynamics, Chalmers, Gothenburg, Sweden
[5]Professor, Linköpings University, Department of Management and Engineering, Linköping Sweden
[6] Specialist whole engine, GKN Aerospace
[7]Founding Director, Institute of System Architectures in Aeronautics, DLR, Hamburg, Germany

Abstract

The goal of this project is to analyse the possibilities offered by different technological solutions to achieve zero emission aviation, firstly in the Swedish/Nordic network context and secondly extend this to the European context. This project will investigate the potential and feasibility of new or upgraded aircraft types based on the different technologies mapped from both, various published roadmaps and national expertise from Swedish aerospace universities and companies. This involves developing aircraft conceptual designs studies and trade analysis with regards to different fuel types, propulsion technologies, structure, operations, network and fleet management, and all relevant technologies. The project will, on a common technology basis, analyse a range of zero carbon fuels and associated technologies through operational studies and optimization to accelerate the introduction of fossil free aircraft technology and choosing optimal paths for making aviation sustainable.

Keywords: Sustainability, Aviation, technology assessment, air travel demand, new aircraft propulsion concepts

1. Introduction

The aviation transport sector emissions are responsible for about 3% of the global emissions; the global air travel and transport industry produced ca. 32.6 billion tons of carbon dioxide emissions from 1940 to 2018 [1]. The CO_2 emission levels from current aircraft operation are well known [4] and fuel economy has been enhanced incrementally over the last decades leading to an eightfold improvement in transport efficiency since the 1960ies [4]. To further put the emissions of aviation into perspective, NOAA and the Atmospheric Environment journal note that carbon dioxide makes up only one-third of aviation emissions [3], while the remaining two-thirds of environmental pollution come from contrails, nitrous oxide (N_2O), water vapor, and other hydrocarbons. These gases have an impact on global warming by increasing radiative forcing, the change in the amount of energy radiated toward the ground [4]. The impact from aviation can therefore not be neglected and new solutions need to be investigated. In this context, achieving the ambitious goals set by Sweden, Fossilfritt flyg 2045 [62] will require extensive development of new solutions; those are bound to technology availability, infrastructure adaption and economic viability.

In a time of new possibilities and the advent of radical zero emission technologies, design revolution leading to new aircraft and propulsion system configurations may pave the way towards future emission free aviation. To understand the possibilities offered by different evolutionary or emergent technologies, architectural choices are reappearing, opening up for an enormous design space in which technology depends on flight operation (networks, fleet design, among other), economics and the environmental footprint. In this context, carefully decisions in which technology to invest in order to create sustainable products in the short and long-term perspective are required.

To understand potential short term (applying state-of-the-art (SotA) technology to start developing a new aircraft), medium term (2035) and long-term (2045) effects, this study will road-map different future operating scenarios based on technology limits, availability, and technology readiness level (TRL), and impact analysis. Such a concept down selection and conceptual design-based study has never been performed before from the Swedish/Nordic perspective. The Nordic region is characterized by a low population density, a relative abundance of smaller airports, and a positive attitude towards new technologies and a high degree of environmental commitment of the society. Similar reports such as Destination 2050 [11] and ICAO Destination Green:The Next Chapter [12] have a global view on the path toward sustainable aviation. The project goal is to provide a roadmap (towards zero emission aviation) for the Swedish/Nordic perspective, providing an open and transparent data set for decision makers for sustainable aviation in Sweden.

2. Demand assessment

The present demand assessment is based on the data made available from Trafikverket, the Swedish Transport Administration [ref]. The data represents a prediction of the Swedish transport demand for 2040. It is divided into four main transportation modes: bus, air transportation, train, and car, each mode split into three categories for work, service, or private purposes. The data record represents all travel demand exceeding 100 km distance in Sweden, resulting in around 79,500 trips spread over the different (12) transportation modes and travelling reasons. It has been chosen to use this data as the prime source of demand for this study. Developing a travel demand model could have been done based on the classic gravity model [5][6][7] and available published projection for population distribution in Sweden and associated economical changes. For the time being, this will not be done here. A simplified approached based on creating different scenarios from Trafikverket data has been chosen instead. The main scenarios are the following:

I. A base line scenario is the data as estimated by Trafikverket.
II. A utopia scenario based on all transport mode re-allocated to flight transport and available airports

From the utopia scenario creation of relevant scenarios based on the available infrastructure, and exclusion of air transport based on time saving and availability of train connection for example

The data available is based on a city/region-to-city/region demand. To address the air transport sector, each city and region has been associated with the nearest airport. The list of available airports is based on currently available airports in Sweden [13], resulting in the generation of 1,594 daily flight trips for 9,542 passengers. The association between cities/regions and airports is based on car travel times, where the shortest time has been considered, excluding any consideration of current air traffic or current airport usage. For Stockholm the repartition is not only based on the distance from city to airport, but a re-distribution based on current distribution between both airport Bromma (ESSB) and Arlanda (ESSA) is used, due to the size difference between both airports. Another approach could consider that travel time to airport, resulting in a much higher frequency from Bromma. In the case of Gothenbourg, the Säve/Gothenborg City Airport (ESGP) has been excluded from the data to maintain the flights operated via Gothenborg Landvetter airport (ESGG). A stricter approach would have been to use only time savings and costs for the consideration of possibilities if airports would re-open for commercial traffic.

Based on the fixed demand assessment, a simplistic fleet approach has been used. For each route the following characteristics are being considered:

- Minimum flight frequency (nr. of aircraft per 24 [hr])
- Load factor (of the used aircraft), and
- Aircraft max. seat capacity

Here, a minimum flight frequency of two is the ground for the work, the load factor considered are 0.5, 0.8 and 0.9. It is assumed that in case the load factor will be below 0.5, the flight frequency should be reduced by 1 or the flight would need subsidiary from region or state to be viable. All daily routes with less than eight passengers have been filtered away. This scenario results in about 160 daily flight routes representing about 8,300 passengers per day. The passenger times distance distribution is presented in Figure 1, where a first fleet allocation can be seen. Note that no considerations to flight feasibility in terms of range of the allocated aircraft are reflected in that figure. The exclusion of about 1,450 daily flight trips only represents 1,200 passengers, about 12% of total daily passenger demand.

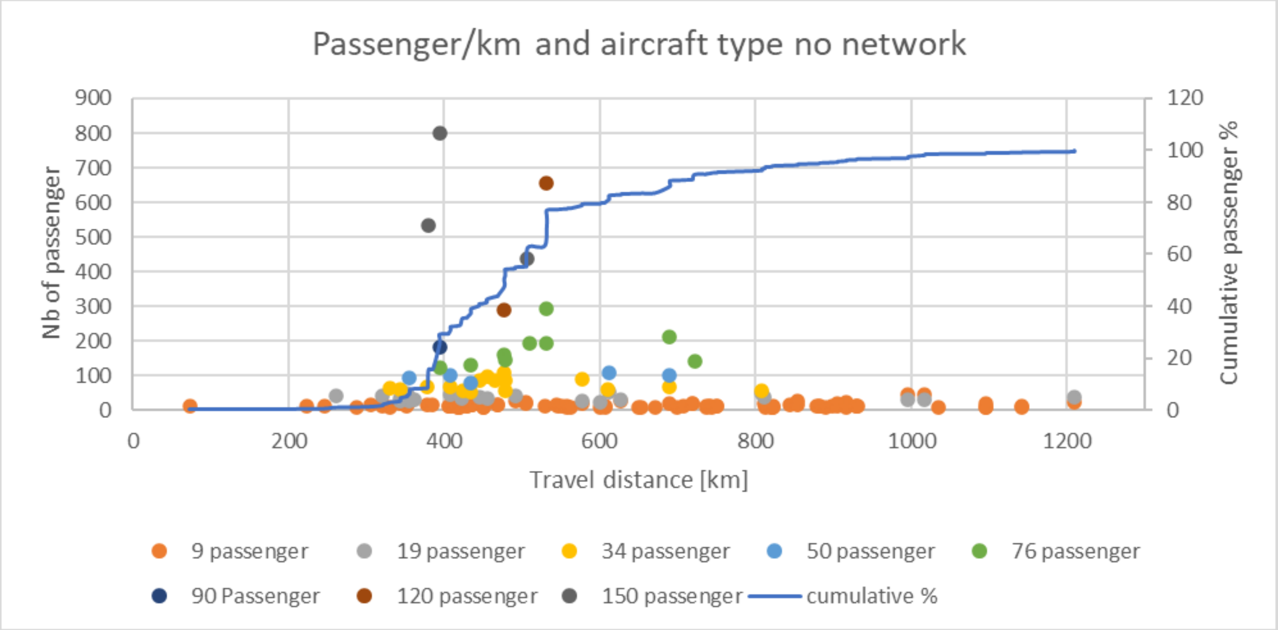


Figure 1: Passenger kilometre and hypothetical associated aircraft type based on point-to-point service

Out from the daily demand, 25 flight routes represent 70% of the total flight demand. Those 25 routes are based on 10 cities, Stockholm, Malmö, Gothenborg, Umeå, Luleå, Ronneby, Ängelholm, Växjö, Åre and Skellefteå, illustrated in Figure 2. It should be noted that the point-to-point demand below eight daily passengers represent ca. 12% (1,166 out of 9,545 passenger) of the total daily passenger demand.

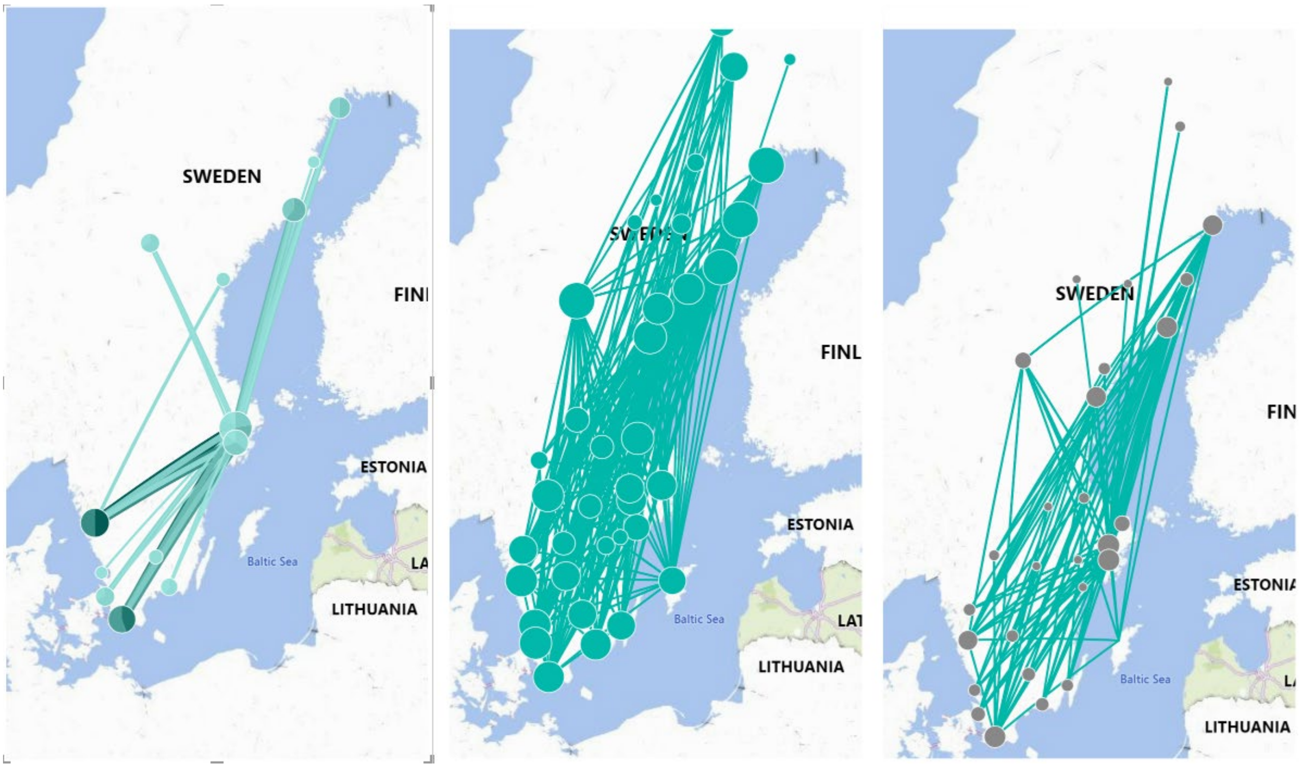


Figure 2: Flight demand in Sweden, represent 70% of all daily passengers (left), all demand for less than 9 passengers (middle), and routes with a demand superior to 9 passengers (right)

The data shows that there is a need to consider a network with some hubs to capture low demand and provide a larger market base. A simple hub approach was selected where the main airports have been selected as possible hubs, and flight with required capacity of 9 passenger has been limited to 450 km and flight with aircraft of capacity of 19 pax have been limited to 550 km. This creates a new redistribution of the different type of aircraft according to Figure 3.

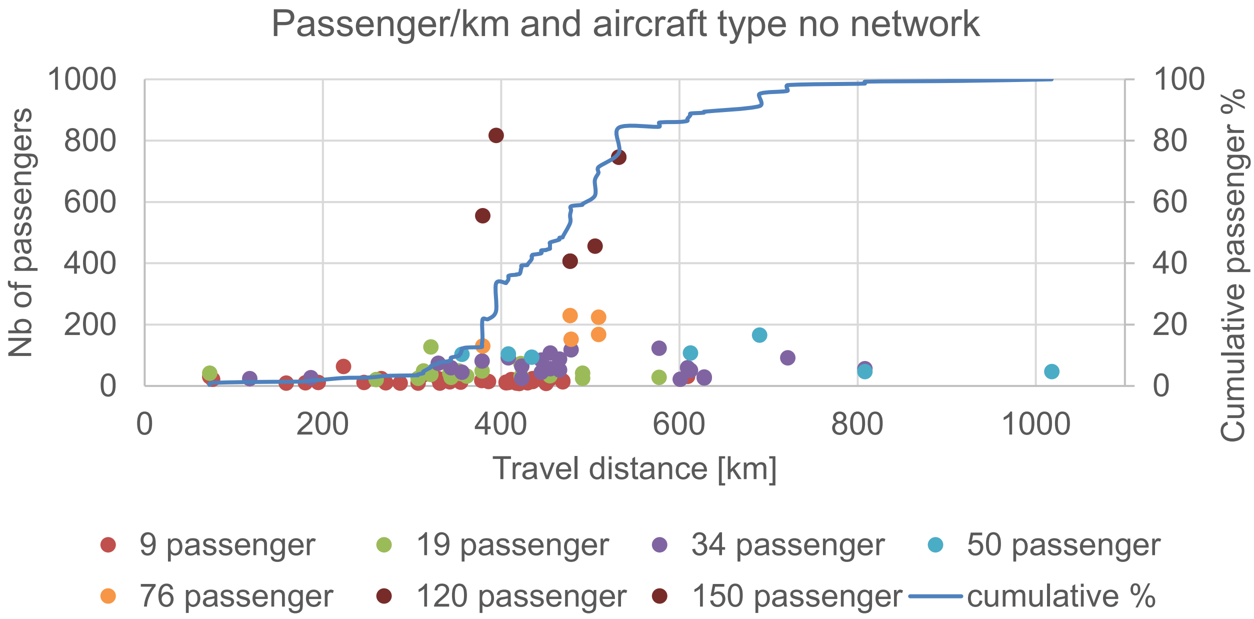


Figure 3 Passenger per kilometre with range limit consideration for 9 and 19 passenger capacity aircraft

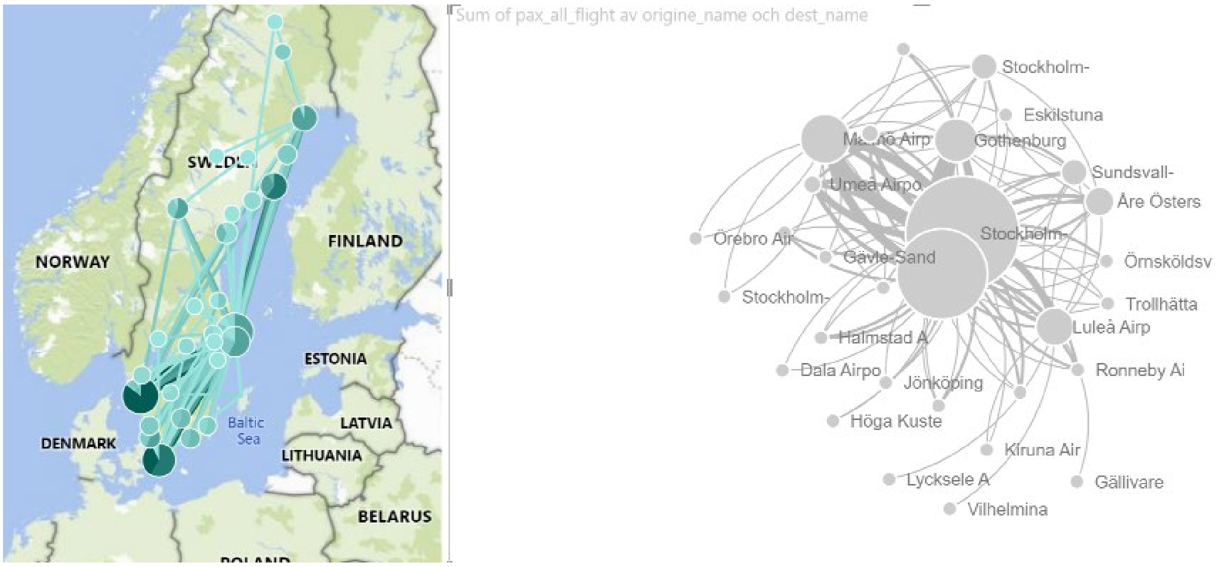


Figure 4 Network based on range limitation for 9 and 19 passenger capacity aircraft

The fleet repartition including the load factors and frequencies for both approaches, the direct flight or hub scenario is presented in Table 1.

Table 1 Aircraft distribution depending on network

	9 Passengers			19 Passengers		34 Passengers			50 Passengers		76 Passengers			90 Passengers	120 Passengers		150 Passengers		
Daily frequency	1	2	3	2	3	1	2	3	1	2	2	3	4	2	3	6	3	4	6
Nb of routes	4	30	7	12	6	6	13	5	2	5	4	5	1	1	1	1	1	1	1
Nb of daily flights	85			42		47			12		27			2	9		13		

	9 Passengers		19 Passengers		34 Passengers		50 Passengers	76 Passengers			90 Passenge	120 Passengers		150 Passengers		
Daily frequency	2	3	2	3	2	3	2	2	3	4	2	3	6	3	4	6
Nb of routes	83	14	15	8	10	6	5	4	4	1	1	1	1	1	1	1
Nb of daily flights	208		54		38		10	24			2	9		13		

3. Aircraft modelling

Different aircraft sizes are being consider as following:

- CS-23 and FAR 23 certifications rules
    - 9 and 19 passengers
- CS-25 and FAR 25 certification rules
    - 34 and 50 passengers,
    - 76 passengers (maximum take of weight of 86,000 lb to respect scope clause [19])
    - 90 passengers
    - 120 and 150 passengers

A notional flight mission is considered to follow a typical commercial flight profile, such as illustrated in Figure 1. Flight reserves are dependent on the certification base and recommendations. For CS-23 following applies:

- VFR: a reserve of 30 or 45 minute applies
- IFR: a reserve of 30 or 45 minutes additional to divergence to the alternate airport

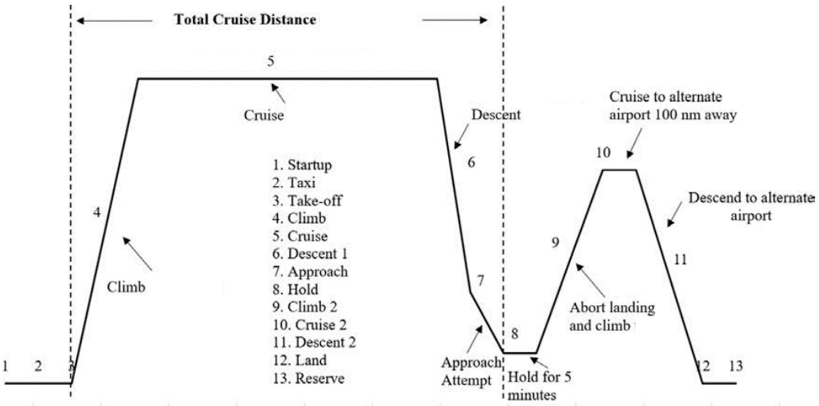


Figure 1: Notional flight mission for commercial aircraft

The aircraft are modelled in a two-step approach. The first modelling, presented in section 3.1 is based on a first principal approach. In a second step, the aircrafts will be modelled in a more detailed way to allow for technology assessments at different levels, which will be performed in a next step. Aircraft that have not been modelled within the project are taken from other studies, see Table 2.

Different main means of propulsion will be study for all those segments, with the goal to provide usable range for each segment and type of propulsion.

For each passenger category, different propulsion technologies are being considered to see their impact on emissions and usable range. The following main propulsion principals and source of energy are considered:

Energy sources:

- Kerosine (Jet A-1) as baseline
- Sustainable aviation fuels (SAF), where the origin and the method to provide/create the SAF must be consider addressing its climate impact
- Hydrogen
    - Direct combustion
    - Fuel cell
- Batteries

The main propulsion principles envisioned are:

- Electrical propulsion
    - Batteries or hydrogen (fuel cell)

- Hybrid
- Direct combustion

Distributed propulsion will be considered when suitable.

3.1 First principia approach

From the demand modelling different categories of aircraft will be created. A summary of the different types and sizes of aircraft variants are presented in the previous chapter. The goal of all those aircraft is to assess the achievable range of a certain size of aircraft in terms of passengers (payload), based on propulsion technologies. The prime modelling will be based on a first order approach with simple assumptions.

The first modelling approach based on Breguet range equations:

$$\boldsymbol{R} = \left(\frac{\Delta h_{fuel}}{g}\cdot\eta\right)\cdot\frac{L}{D}\cdot\ln\left(\frac{1}{1-\frac{m_{fuel}}{M_{TOW}}}\right) \qquad (1)$$

Where Δh_{fuel} is the fuel specific energy. Equation 1 is the Breguet range equation for aircraft whose fuel mass depletes during flight. For aircraft with fixed mass energy sources i.e., battery powered aircraft, equation 2 applies.

$$\boldsymbol{R} = \left(\frac{E_{battery}}{g}\cdot\eta\right)\cdot\frac{L}{D}\cdot\frac{m_{battery}}{M_{TOW}} \qquad (2)$$

The total mass of the aircraft can be extracted from Equation 3:

$$1 = \frac{m_{empty}}{M_{TOW}} + \frac{m_{payload}}{M_{TOW}} + \frac{m_{fuel\,or\,battery}}{M_{TOW}} \qquad (3)$$

The different weight fractions are based on statistics from existing aircraft. It is assumed that some agreement between empty weight (m_{empty}) and maximum take of weight (M_{TOW}) -- representing the structural efficiency of the aircraft -- will remain in the same order for future aircraft. This could certainly be changed and influenced by technology choices but is viewed as a valid first approach. In a refinement model of the different aircraft this technology-dependent weight fraction change will be addressed. The weight fraction statistic for a certain number of known aircraft are displayed in Figure 2.

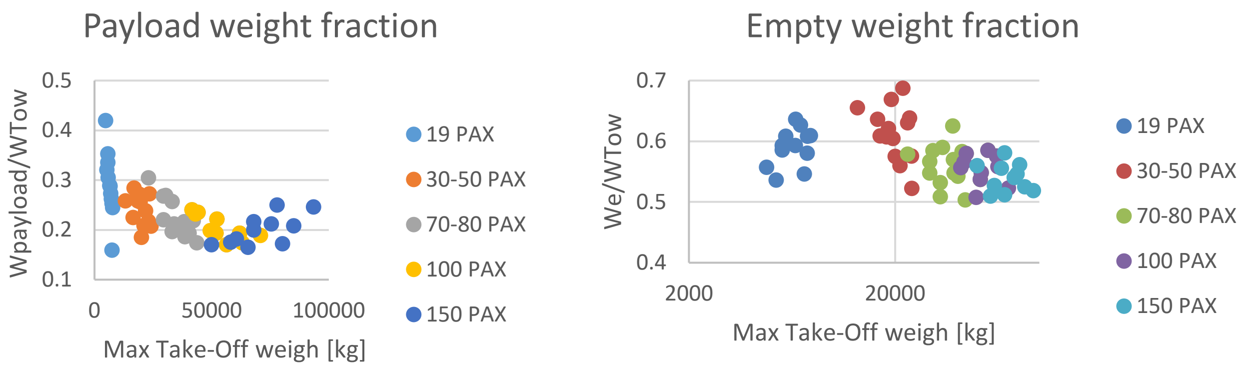


Figure 2: Passenger and empty weight fraction as a function of maximum take-off weight

The specific energy of the different energy sources is presented in Tabel 1. Note that there is an interval considered for the batteries. This interval represents batteries cell with about 320 Wh/kg to 1000 Wh/kg. Note that the numbers are on cell level only and do not represent the operational usable specific energy, installation (packaging), cycle life and other parameters [20][21]. For hydrogen and kerosene, a storage volumetric constrain will have an impact on what can be considered as the usable energy. To take that into account, a gravimetric efficiency is introduced, based on study from ATI [18]. In the detail study, this gravimetric efficiency will be replaced and modelled by models of the tanks and the fuel system.

Tabel 1 Specific energy for different energy sources

	Units	Hydrogen	Kerosene	Battery
Specific Energy	MJ/kg	~140	~46	0.9-3.6
Gravimetric efficiency	%	60	98	

Assumptions on the lift-to-drag ratio (L/D) shown in Figure 3, is taken from statistics data from [15]. Based on existing aircraft, this data set does (of course) not consider distributed propulsion concepts.

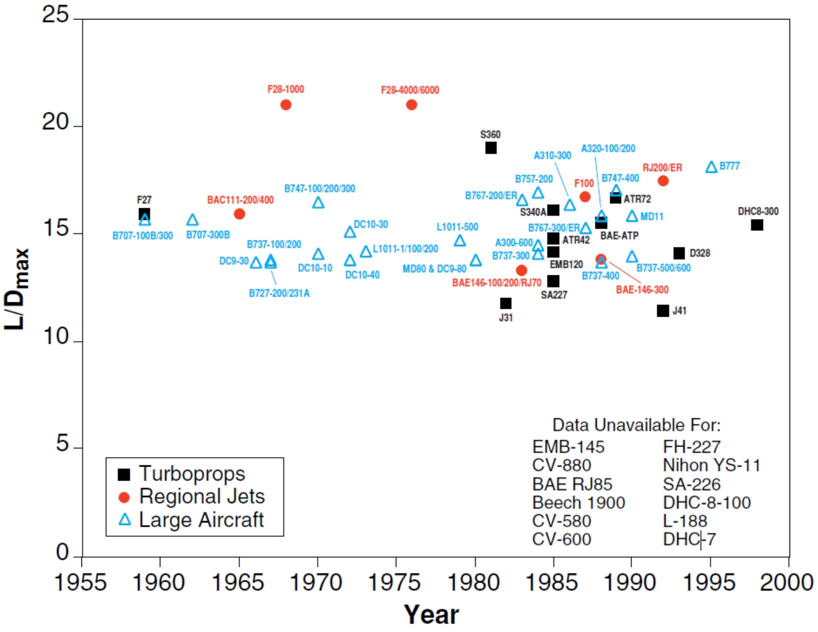


Figure 3: Aircraft L/D statistic for cruise. Data from Babikian [15]

Apply the first principia approach allow the creation of notional range based on the application of the above-described formulas. By applying the average typical weight fractions from statistical aircraft notional range for the different aircraft energy sources can be apply, those notional ranges do not include reserve or any consideration to other flight segment than cruise or system power demand. In Figure 4 a lift-to-drag ratio of 16 is applied, the yellow band represent the typical variation between the different aircraft classes. All values for batteries are reflecting power at pack level, here 200, 500, and 800 Wh/kg respectively.

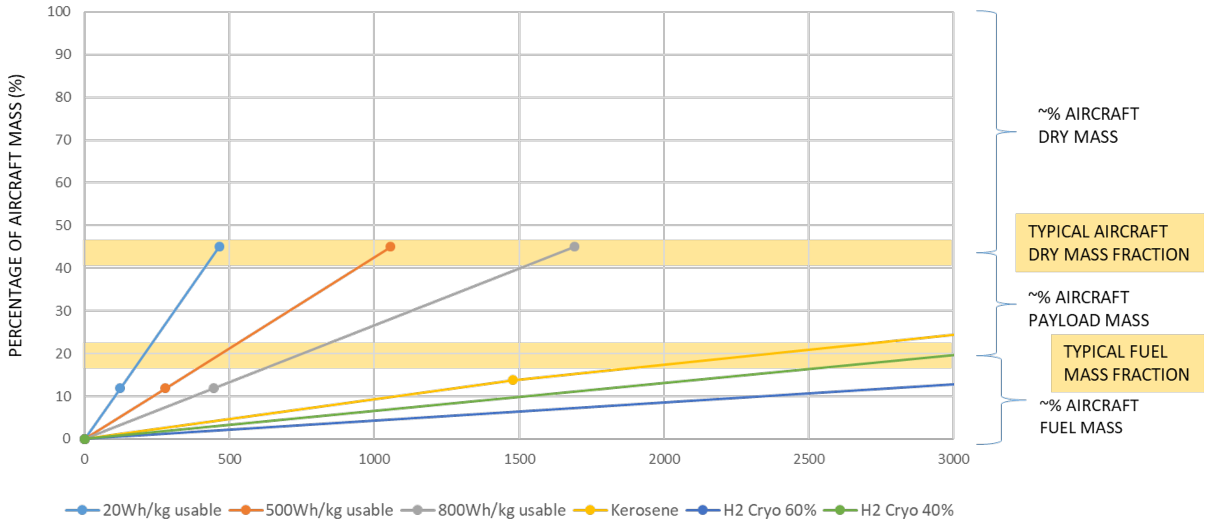


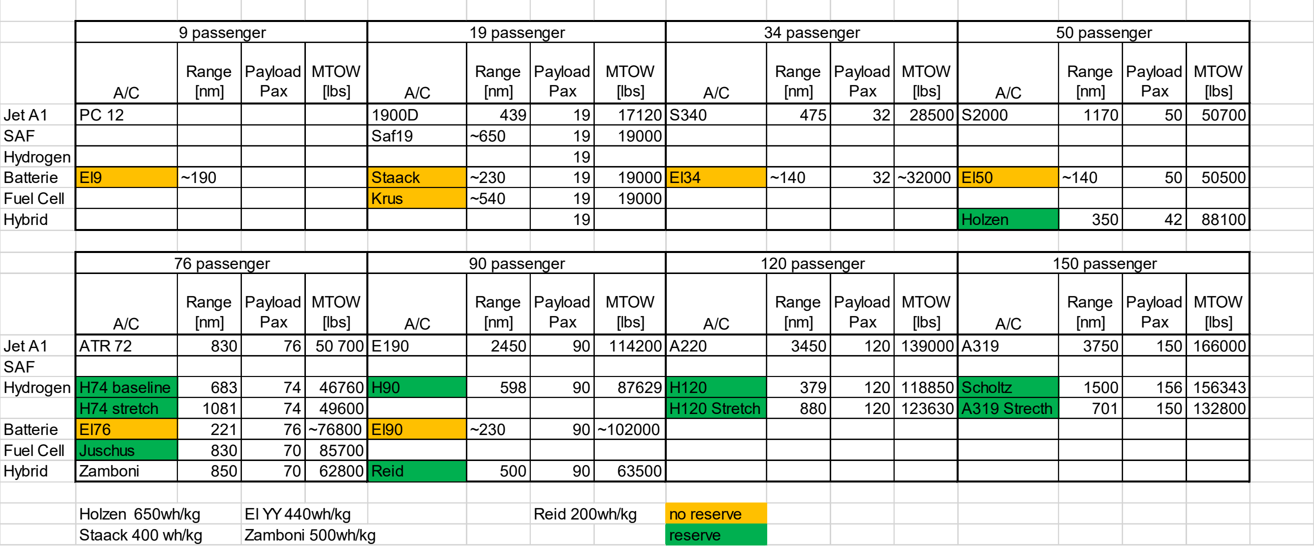
Figure 4: Fuel and tank storage mass as well as payload mass fractions vs aircraft range diagram

3.2 More detailed modelling

Some aircraft are model in Pacelab SysArc. Pacelab SysArc [56] provides a fully parametric object-oriented aircraft definition, created from customizable data objects, so-called EO Concepts that are used not only to build and specify the aircraft assembly (wing, fuselage, propulsion system, etc.) but also its mission, performance estimations, aerodynamic characteristics, payload, and onboard systems. Therefore, one method that has been employed to achieve the required variation across all design alternatives was to manipulate selected parameters, for instance to change size/weight/position of components. Hydrogen powered aircraft have been designed. The design approach has been to use the build in capabilities and weight equations, in order to include the hydrogen propulsion a tank model has been developed and integrated. The cryogenic tank model includes both the mechanical design considering internal over-pressure and thermal design which takes heat transfer via conduction, convection and radiation between the tank and the environment with a varying contact surface into account. Dynamics of the liquid hydrogen storage, in terms of internal pressure, heat transferred and venting rate over time, are also calculated. The dynamic characteristics could be important in mission performance analyses however not included in the current preliminary designs. Aluminium alloy 2219 has been assumed to be used as the main material for the tank. Lightweight polyurethane foam insulation has been considered in the preliminary designs. The use of other insulation design, i.e., multi-layer insulation or vacuum insulation, can be open in the later stage of the study. The propulsion is based on direct combustion, where the specific fuel consumption (SFC) is adjusted for the higher specific power of hydrogen. Only liquid hydrogen is considered here. The goal of this models is to enable technology infusion to address the viability and the possibilities offered by them. This will be completed in on-going work. The parametric models created will allow a more granular modelling of the different concepts and propulsion alternatives and will open-up for technology assessments, as presented in [16] and [17].

The results from the aircraft modelling are summarised in Table 2, note that it is hard to directly compare any data; the values are to be representative.

Table 2 Different aircraft concept modelled and from literature [50][51][52][53][54][49]



	9 passenger				19 passenger				34 passenger				50 passenger			
	A/C	Range [nm]	Payload Pax	MTOW [lbs]	A/C	Range [nm]	Payload Pax	MTOW [lbs]	A/C	Range [nm]	Payload Pax	MTOW [lbs]	A/C	Range [nm]	Payload Pax	MTOW [lbs]
Jet A1	PC 12				1900D	439	19	17120	S340	475	32	28500	S2000	1170	50	50700
SAF					Saf19	~650	19	19000								
Hydrogen							19									
Batterie	🟨 El9	~190			🟨 Staack	~230	19	19000	🟨 El34	~140	32	~32000	🟨 El50	~140	50	50500
Fuel Cell					🟨 Krus	~540	19	19000								
Hybrid							19						🟩 Holzen	350	42	88100

	76 passenger				90 passenger				120 passenger				150 passenger			
	A/C	Range [nm]	Payload Pax	MTOW [lbs]	A/C	Range [nm]	Payload Pax	MTOW [lbs]	A/C	Range [nm]	Payload Pax	MTOW [lbs]	A/C	Range [nm]	Payload Pax	MTOW [lbs]
Jet A1	ATR 72	830	76	50 700	E190	2450	90	114200	A220	3450	120	139000	A319	3750	150	166000
SAF																
Hydrogen	🟩 H74 baseline	683	74	46760	🟩 H90	598	90	87629	🟩 H120	379	120	118850	🟩 Scholtz	1500	156	156343
	🟩 H74 stretch	1081	74	49600					🟩 H120 Stretch	880	120	123630	🟩 A319 Strecth	701	150	132800
Batterie	🟨 El76	221	76	~76800	🟨 El90	~230		90	~102000							
Fuel Cell	🟩 Juschus	830	70	85700												
Hybrid	Zamboni	850	70	62800	🟩 Reid	500	90	63500								

Holzen 650wh/kg
El YY 440wh/kg
Reid 200wh/kg
🟨 no reserve
Staack 400 wh/kg
Zamboni 500wh/kg
🟩 reserve

4. Technologies

Here main technologies that will affect the different aircraft design are summarized, the goal is to give an overview and describe how they will benefit a sustainable roadmap for Swedish air transport. Many reports describing forecasted technologies can be founded, such as Destination 2050 [32], IACO [33] and NASA N+3[43][42] and N+4[41] reports among others. Only some of them are highlighted there. It should be noted that technology to reach sustainability for Swedish aviation 2045 cannot be technologies that would be available 2045. Current aircraft would need to be entire replaced by 2045 to have an entire fleet that respond to sustainability criteria, typically leading to a need of developing new aircraft based on today's state of the art technology and the technology that would be available within the coming 10-15 years.

4.1 Battery

Battery development is a key for electrical flight, the identified main parameters for battery are specific energy density, specific energy, life cycles, and discharge/charge rates

Current battery development is mainly driven by the EV demands, specification for the automotive industries have been described by EUCAR [22], EUROBAT [23], European commission [24] among other. The current state of the art from the main characteristic of interest Wh/kg is about 250-300 Wh/kg at pack level, expected for 2030 is about 500-600 Wh/kg at cell level with a reduction of 20% at pack level, according to [24]. Other chemistries, describe in [28][29][30] show higher numbers but status and future availability are unclear. Evolution of batteries in the automotive sector as presented in Figure 5, present at best a yearly improvement of 4,8% if the hugest value in the picture is used, if the projection of SDI type of battery is used the yearly progression is about 4.1%.

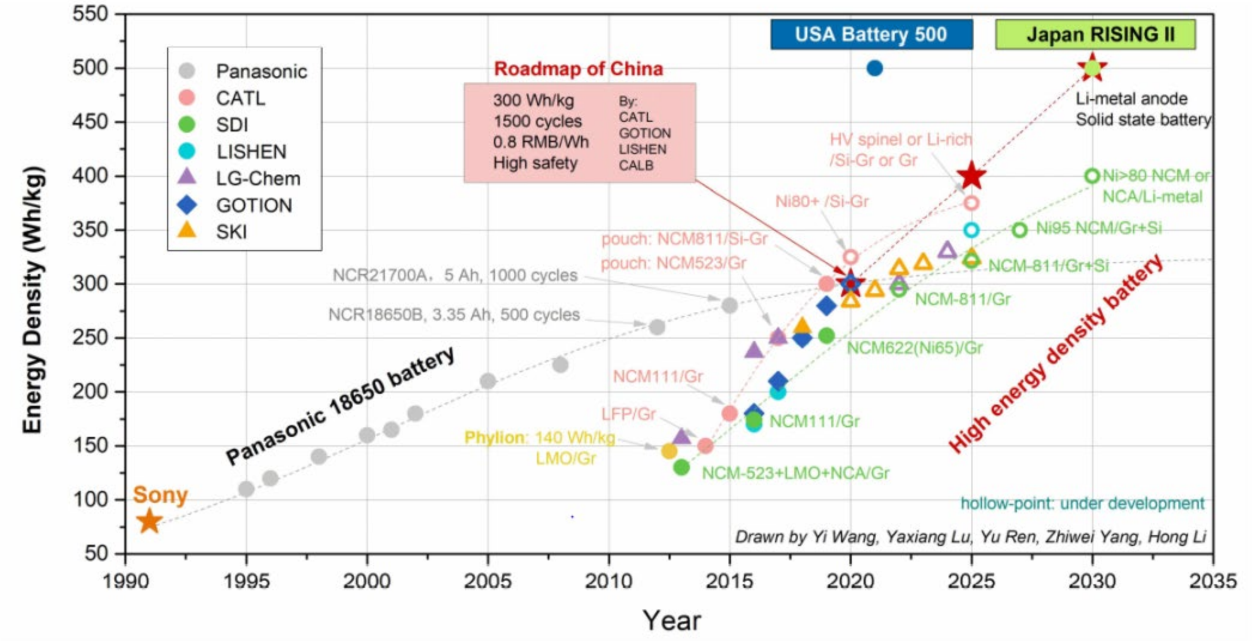


Figure 5Comparison of the gravimetric performance of different batteries for automotive applications [23]

The present study corroborate with other studies, such as [25][26] [31] [27][31], that depending on the aircraft categories the battery energy density required for aircraft start at around 500-600 Wh/kg at the pack level, unless very short range are targeted. Current battery research indicates that with a yearly increase of 4,8%, cell levels will be around 600 Wh/kg, unless a radical new battery type appears before. Technology available 2035 will typically represent battery that can be integrate into an aircraft and into service for about 2040, if a notional 5 years of certification of a new battery type is considered.

4.2 SAF

Sustainable aviation fuel are alternative aviation fuels divided into different categories: bio-jet fuels (produced from biomass), synthetic jet fuels (produced from natural gas and coal), liquefied gas from natural gas (LNG) or non-natural gas, liquefied hydrogen (LH2), electro fuels, and electricity. Here only biofuel and hydrogen are addressed; a more comprehensive overview of sustainable aviation fuel is described by Dahal[55].

4.2.1 Biofuel

Experiment flight with bio-jet fuels have already been performed by several airlines around the world, development and commercialization is on-going [63]. From an aircraft development perspective, the adoption of bio-jet fuels has a small or even no impact on the engine design. Adoption of 100% bio-jet fuel will be require retrofitting and development of new engine. From an aircraft performance standpoint the biofuel will provide similar performance as today's fuel. Sustainable aviation will still produce water vapour, NO_x and CO_2 [64][65][66], part of the emitted CO_2 will be counterbalanced by the production. In general, the key challenges of biofuels are the availability of sustainable feedstock and the production costs. Expansion of biofuels can cause negative environmental effects such as direct and indirect land use changes, deforestation, water depletion, and loss of biodiversity and may compete with food production, requiring policies for energy, land use, water management, and the use of sustainable biomass resources [67].

4.2.2 Hydrogen

Hydrogen is identified as a potential mean of reducing aviation climate impact. Many reports and initiatives in Europe [32] and worldwide [33] are focusing on hydrogen for aircraft energy sources. From an energy perspective, hydrogen is attractive with a high specific energy density, and a hydrocarbon-free combustion. Depending on the type and size of aircraft, two main system installations, fuel cell or direct combustion, are possible. However, as with any technology, there are some drawbacks. Hydrogen has a low volumetric energy density, leading to larger tank (and aircraft) volume. The volume-optimal SotA hydrogen storage solution is a cryogenic liquid tank, where the tank gravimetric efficiency (η) can be expressed as:

$$\eta_{grav} = \frac{m_{H2}}{m_{tank+m_{insulation}+m_{H2}}}$$

The gravimetric efficiency for the hydrogen storage is a key enabler for hydrogen aircraft. From an aircraft development perspective also other challenges exist, such as fuel system architecture and installation, insulation, configuration, and safety aspects. Other barriers are coming from economical perspective addressed by Dahal [55], cost of hydrogen and its impact on direct operating cost. Infrastructure will be impacted and need to adapt; infrastructural changes have often long lead times and will only be initiated if a certain confidence, clear policies, and market opportunities exist [60][61].

The hydrogen supply chain and production is another main challenge that Hoelzen [61] describes and quantifies. To be sustainable, so-called "well-to-wing" analyses are of highest importance, the production of hydrogen must be sustainable to enable a CO_2 emission free aviation.

4.3 Structure

Structural improvements, leading to weight reduction, is see as a key enabler to higher efficiency in aircraft energy demand [41][42][43]. Higher usage of composite [40] and multifunctional material has the potential of reducing weight. Some considered technologies are: advanced metallic structural and subsystem alloys, ultra-high performance fibre [39], nano engineered structures, affordable large integrated structures [35][36], integrated aero-servo-elastic structures [37][38], multifunctional structures [36], and airframe design load reduction from gust load alleviation and health monitoring.

4.4 Aerodynamic

Many improvements are foreseen to be accomplishes in terms of aerodynamic: progress in laminar flow [44][45][46] demonstrated e.g., by Clean Sky BLADE [47] show important improvement in terms of drag reduction. This could also be combined with higher aspect ratio wings, reducing induced drag, if innovative load and flight control can be realised [42][43]. However, high aspect ratio wings are limited by airport space and therefore folding wings technologies may need to be considered on certain type of aircraft.

Improvements in product development engineering and multidisciplinary optimization can help in the development of new aircraft. Recent progress within this domain [43][57][58] enables an earlier adoption and faster usage of such approaches in earlier concept development and are therefore beneficial.

4.5 Operation

One important area to consider when addressing future of aviation are operational aspects. Typically, economics and maintenance are important topics when it comes to operation but are not addressed here. One important area for future operation from a Swedish perspective, is the usage of small local/rural airports with less traffic, such as describe in the demand assessment of Sweden in

Chapter 2. To foster the usage of those airports, improvements on air traffic management (ATM) e.g., offered by the remote tower concept must be included [68]. Modern ATM will also help in better planning and more optimal routes; SESAR/Singel European Sky [69] is an example of an European project with large energy saving potential.

Other important aspects such as all-weather capabilities and possibilities to land in bad weather and low visibility are key enablers for some concepts. Solutions such as the enhanced flight vision system (EFVS) are available [34]. Other operational and organisational aspects such as passenger time at airport and boarding procedures must be in adequation with the usage of small local airports. Other important factor to enable cost efficient operation would be the possibility offered by single pilot operation. Finally, depending on the type of energy source, the airport infrastructure will need to be updated in accordance. Typically, infrastructure changes are time consuming and need long term planning to be on place when new type of aircraft start operation.

5. Results and conclusions

The preliminary results indicates that only few routes represent 70% of the total inner Swedish air transport demand. Those routes are to some extend in direct competition with train services, examples being Stockholm-Gothenbourg and Stockholm-Malmö. The different scenarios described in Chapter 2 lead to two types of fleet distribution presented in Table 1. Based on the range and type of aircraft described in the fleet allocation and the different aircraft type modelled within Chapter 3, it can be concluded that a mix of solutions is needed for the inner Swedish air transport demand. However, it is very reductive only considering Sweden; a broader international view should be pointed out. The main difference between Sweden and most published roadmaps and studies on sustainable aviation is the relatively small market and hence a different type of operational requirements. Considering the data presented there is a large need for smaller regional aircraft. These identified routes are typically not served today, mainly due to economic reasons. The realisation of the scenario described in this work are therefore very sensitive to the economic viability of smaller commuter aircraft. Realisation of the small type of all-electrical aircraft with a sufficient range to serve the total Swedish demand is considered to be hard to reach, mainly due to battery limitations. A technical leap in battery characteristics is needed; the currently 4-5% yearly improvements are not sufficient to create that. For regional aircraft, different solution may be viable such has hybrid propulsion or hydrogen-based propulsion.

6. Future work

In order to complete this work a follow-up work is on-going with the goal to complete this work with the assessment of different scenarios and timelines for the introduction of new aircraft types and concepts and how this will lead to a fossil-free Swedish aviation by 2045. Economics must be included for different aspects: on the demand model, where the introduction of new possibilities for flight routes will be coupled with the economy associated to it, and from an operator- and passenger perspective, coupling the cost of the energy sources. Due to the relatively small Swedish market an extension to whole Scandinavian area and the Baltic Sea countries is needed. The technology presented here will be infused to the different aircraft models that have been created to improve and enable a better assessment on their impact.

7. Contact Author Email Address

mailto: christopher.jouannet@saabgroup.com
mailto: anders.lundbladh@gkn.com
mailto: ingo.staack@liu.se
mailto: tomas.gronstedt@chalmers.se
mailto: xin.zhao@chalmers.se
mailto: petter.krus@liu.se
mailto: bjoern.nagel@dlr.de

8. Acknowledgement

The authors would like to acknowledge the Swedish Energy Agency for its financial support through the grant 2021-015938.

9. Copyright Statement

References

[1] Ritchie, H. "Climate change and flying: what share of global CO2 emissions come from aviation," Our World in Data, Vol. 22, 2020.

[2] Claire, B. and Josh, M. "Transport could burn up the EU's entire carbon budget," Online, 2021.

[3] NOAA. "Aviation is responsible for 3.5 percent of climate change, study finds," September 2020.

[4] Lee, D. S., Fahey, D., Skowron, A., Allen, M., Burkhardt, U., Chen, Q., Doherty, S., Freeman, S., Forster, P., Fuglestvedt, J., et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," Atmospheric Environment, Vol. 244, 2021, pp. 117834.

[5] McNally, M. G. "The four-step model," *Handbook of transport modelling*. Vol. 1, Emerald Group Publishing Limited, pp. 35-53, 2007. https://doi.org/10.1108/9780857245670-003

[6] Donnelly, R. *Advanced practices in travel forecasting,* Vol. 406, Transportation Research Board, 2010. https://doi.org/10.17226/22950

[7] Justin, C. Y., Payan, A. P., and Mavris, D. "Demand modeling and operations optimization for advanced regional air mobility," *AIAA Aviation 2021 Forum*, pp. 3179, 2021. https://doi.org/10.2514/6.2021-3179

[8] Roy, S., Kotwicz Herniczek, M. T., German, B. J., and Garrow, L. A. "User base estimation methodology for a business airport shuttle air taxi service," *Journal of Air Transportation*, Vol. 29, No. 2, pp. 69–79, 2020. https://doi.org/10.2514/1.D0216

[9] Boehm, Randall C., Scholla, Logan C., et Heyne, Joshua S. Sustainable alternative fuel effects on energy consumption of jet engines. *Fuel*, vol. 304, p. 121378, 2021.

[10] Westenberger, A. *Liquid Hydrogen fuelled aircraft - System Analysis, Final Technical Report (Publishable version)*. Cryoplane project, 2003.

[11] www.destination2050.eu (Accessed on 2022-01-23)

[12] www.icao.int/environmental-protection/pages/ENVrep2019.aspx (Accessed on 2022-05-25)

[13] https://www.lfv.se/om-oss/sveriges-flygplatser (Accessed on 2022-05-25)

[14] https://www.flygplatser.se/ (Accessed on 2022-05-25)

[15] Babikian R., *The historical fuel efficiency characteristics of regional Aircraft from technological, operational and cost perspective*, SM Thesis, MIT, June 2001

[16] Jouannet, C., Amadori, K., Bäckström, E., and Bianchi, D., "Uncertainty Management in Technologies Prioritization for Future Aircraft Program," AIAA Scitech 2020 Forum, AIAA-2020-0019, Orlando, FL, 2020

[17] Bianchi,D., Amadori, K., Bäckström, E., Jouannet, C. and Secco, N., "An Uncertainty-based Framework for Technology Portfolio Selection for Future Aircraft Program," AIAA Scitech 2021 Forum, AIAA-2021-1479, 2021

[18] Realising Zero-Carbon emission flight, Primary Energy Source Comparison and Selection, ATI

[19] https://en.wikipedia.org/wiki/Scope_clause

[20] Ajay Misra. Energy storage for electrified aircraft: The need for better batteries, fuel cells, and supercapacitors. IEEE Electrification Magazine, 6(3):54–61, Sep. 2018.

[21] Aircraft Electric Propulsion and Power Working Group - AIAA. Guidelines for Analysis of Hybrid Electric Aircraft System Studies, 2019

[22] https://www.eucar.be/battery-requirements-for-future-automotive-applications/

[23] https://www.eurobat.org/wp-content/uploads/2022/03/EUROBAT_Battery_Innovation_Roadmap_2030_White_Paper.pdf

[24] https://ec.europa.eu/energy/sites/ener/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf

[25] Schäfer, A.W., Barrett, S.R.H., Doyme, K. et al. (2019), Technological, economic and environmental prospects of all-electric aircraft. Nat Energy 4, 160–166.

[26] Viswanathan, V., Epstein, A.H., Chiang, YM. et al. The challenges and opportunities of battery-powered flight. Nature 601, 519–525 (2022). https://doi.org/10.1038/s41586-021-04139-1

[27] B. J. Brelje and J. R. R. A. Martins. Electric, Hybrid, and Turboelectric Fixed-Wing Aircraft: A Review of Concepts, Models, and Design Approaches, Progress in Aerospace Sciences, 104:1–19, January 2019. doi:10.1016/j.paerosci.2018.06.004

[28] Wenzhuo Cao, Jienan Zhang, Hong Li, Batteries with high theoretical energy densities, Energy Storage Materials, Volume 26, 2020, Pages 46-55, ISSN 2405-8297, https://doi.org/10.1016/j.ensm.2019.12.024.

[29] Fichtner, M., Edström, K., Ayerbe, E., Berecibar, M., Bhowmik, A., Castelli, I. E., Clark, S., Dominko, R., Erakca, M., Franco, A. A., Grimaud, A., Horstmann, B., Latz, A., Lorrmann, H., Meeus, M., Narayan, R., Pammer, F.,

Ruhland, J., Stein, H., Vegge, T., Weil, M., Rechargeable Batteries of the Future—The State of the Art from a BATTERY 2030+ Perspective. Adv. Energy Mater. 2022, 12, 2102904. https://doi.org/10.1002/aenm.202102904

[30]Michel Armand, Peter Axmann, Dominic Bresser, Mark Copley, Kristina Edström, Christian Ekberg, Dominique Guyomard, Bernard Lestriez, Petr Novák, Martina Petranikova, Willy Porcher, Sigita Trabesinger, Margret Wohlfahrt-Mehrens, Heng Zhang, Lithium-ion batteries – Current state of the art and anticipated developments, Journal of Power Sources,Volume 479, 2020, 228708, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2020.228708.

[31]Staack, I., Sobron, A. & Krus, P. The potential of full-electric aircraft for civil transportation: from the Breguet range equation to operational aspects. CEAS Aeronaut J 12, 803–819 (2021). https://doi.org/10.1007/s13272-021-00530-w

[32]https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf

[33]https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg24-38.pdf

[34]https://www.saab.com/newsroom/press-releases/2019/saab-and-v-systems-launch-game-changing-enhanced-flight-vision-system-solution

[35]http://www.locomachs.eu/

[36]http://www.saristu.eu/downloads/dissemination-material/

[37]Shirk, M., Hertz, T., and Weisshaar, T., " Aeroelastic Tailoring – Theory, Practice, and Promise, " Journal of Aircraft, Vol. 23, No. 1, pp. 6-18, Jan. 1986.

[38] Shirk, M.H., Hertz, T.J., and Weisshaar, T.A., " Aeroelastic Tailoring – Theory, Practice, and Promise, " AIAA/ASME/ASCE/AHS 25th Structures, Structural Dynamics and Materials Conference, Palm Springs, CA, AIAA 1984-0982.

[39]Cunniff, P., Auerbach, M., Vetter, E., and Sikkema, D., " High Performance M5 Fiber for Ballistics/Structural Composites, " 23rd Army Science Conference, Orlando, Florida, AO-04, 2004.

[40]Miller, A., " Ideas on How AMTAS Can Support the Aviation Industry (and More), " Advanced Materials in Transport Aircraft Structures (AMTAS) Spring 2005 Meeting, 2005.

[41]Bradley, M. K. and Droney, C. K.; Subsonic Ultra Green Aircraft Research: Phase I Final Report; NASA/CR–2011-216847

[42]E.M. Greitzer, et. al. ; N+3 Aircraft Concept Designs and Trade Studies, Final Report Volume 2: Appendices—Design Methodologies for Aerodynamics, Structures, Weight, and Thermodynamic Cycles, NASA/CR—2010-216794/VOL2

[43]Bruner S., et. Al.; NASA N+3 Subsonic Fixed Wing Silent Efficient Low-Emissions Commercial Transport (SELECT) Vehicle Study Revision A; NASA/CR—2010-216798

[44]Fuhrmann, H., " Application of Natural Laminar Flow to a Supersonic Transport Concept, " AIAA 1993-3467.

[45]Crouch, J., " Modeling Transition Physics for Laminar Flow Control, " 38th Fluid Dynamics Conference and Exhibit, Seattle, Washington, AIAA 2008-3832.

[46]Solomon, W. D., Drake, A., Reed, H. & Saric, W., 2004. Design and Testing of a 30-Degree Sweep Laminar Flow Wing for a High Altitude Long-Endurance Aircraft, s.l.: RTO-MP-AVT-111

[47]Williams, G., "Aerospace Technology Demonstration: BLADE, the Flagship Laminar Flow Project within the Clean Sky Programme," SAE Technical Paper 2017-01-2016, 2017, https://doi.org/10.4271/2017-01-2016.

[48]Hoelzen, J.; Liu, Y.; Bensmann, B.; Winnefeld, C.; Elham, A.; Friedrichs, J.; Hanke-Rauschenbach, R. Conceptual Design of Operation Strategies for Hybrid Electric Aircraft. *Energies* **2018**, *11*, 217. https://doi.org/10.3390/en11010217

[49]Zamboni J.,Vos R; Emeneth M and Schneegans A."A Method for the Conceptual Design of Hybrid Electric Aircraft," AIAA 2019-1587. *AIAA Scitech 2019 Forum*. January 2019.

[50]Krus P.; Staack I. and Olivieira A.; Hybrid electric propulsion system optimization for a commuter aircraft, ICAS 2022, Stockholm Sweden

[51]J. Hoelzen, D. Silberhorn, T. Zill, B. Bensmann, R. Hanke-Rauschenbach, Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps, International Journal of Hydrogen Energy, Volume 47, Issue 5, 2022, Pages 3108-3130, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.10.239.

[52]Juschus D.; Preliminary Propulsion System Sizing Methods for PEM Fuel Cell Aircraft; Master Thesis, TU Delft, 2021; http://resolver.tudelft.nl/uuid:fdc14875-175e-4a4b-8cde-f2f4b6028194

[53]Reid S. J.; Hybrid electric regional aircraft design with optimal power management; Master Thesis, Royal Military College of Canada, March 2022

[54]Scholz D.; Design of Hydrogen Passenger Aircraft – How much "Zero-Emission" is Possible?; Hamburg Aerospace Lecture Series (DGLR, RAeS, VDI, ZAL, HAW Hamburg), Hamburg, Germany, 2020-11-19; https://doi.org/10.5281/zenodo.4301103

[55]K. Dahal, S. Brynolf, C. Xisto, J. Hansson, M. Grahn, T. Grönstedt, M. Lehtveer, "Techno-economic review of alternative fuels and propulsion systems for the aviation sector", Renewable and Sustainable Energy Reviews", Volume 151, 2021, 111564, ISSN 1364-0321,

[56]PaceLab Suite https://pace.txtgroup.com/products/preliminary-design/pacelab-suite/

[57]L. Boggero and P. D. Ciampa and B. Nagel; The Application of the AGILE4.0 MBSE Architectural Framework for the Modeling of System Stakeholders, Needs and Requirements; ICAS 2021, doi:10.5281/zenodo.5735416

[58]P. D. Ciampa and B. Nagel; Accelerating the Development of Complex Systems in Aeronautics via MBSE and MDAO: a Roadmap to Agility; AIAA Avition 2021, AIAA-2021-3056; https://doi.org/10.2514/6.2021-3056

[59]A hydrogen strategy for a climate-neutral Europe, European commission, 2020, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

[60]Breitschopf, B., Zheng, L., Plaisir, M.; European Commission, Directorate-General for Energy, The role of renewable H_2 import & storage to scale up the EU deployment of renewable H_2 : report, (2022).https://data.europa.eu/doi/10.2833/727785

[61]J. Hoelzen, D. Silberhorn, T. Zill, B. Bensmann, R. Hanke-Rauschenbach, Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps,International Journal of Hydrogen Energy, Volume 47, Issue 5, 2022,Pages 3108-3130, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.10.239

[62] https://fossilfrittsverige.se/en/roadmap/the-aviation-industry/

[63] Wei-Cheng Wang, Ling Tao, Bio-jet fuel conversion technologies, Renewable and Sustainable Energy Reviews, Volume 53, 2016, Pages 801-822, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2015.09.016

[64]Starik AM, et al. Analysis of emission characteristics of gas turbine engines with some alternative fuels. Int J Green Energy 2018;15(3):161–8.

[65] Gaspar RMP, Sousa JMM. Impact of alternative fuels on the operational and environmental performance of a small turbofan engine, vol. 130; 2016. p. 90.

[66] Schripp T, et al. Particle emissions of two unblended alternative jet fuels in a full scale jet engine. 2019. p. 256. Fuel

[67] Popp J, et al. The effect of bioenergy expansion: food, energy, and environment. Renew Sustain Energy Rev 2014;32:559–78.

[68] https://www.remote-tower.eu/wp/, online (Accessed 2022-05-27)

[69] https://www.sesarju.eu/, online (Accessed 2022-05-27)