SUSTAINABLE AVIATION IN NORDIC COUNTRIES

Christopher Jouannet[1], Kristian Amadori[2], Erick Espinoza Juarez[3]

[1]Associated Professor, Linköpings University, Sweden, Christopher.jouannet@liu.se
[2]Docent, Linköpings University, Sweden
[3]Research assistant, Linköpings University. Sweden

Abstract

Domestic flights in Sweden and the Nordic region face a major challenge to become climate-neutral by 2045. The project has investigated how different propulsion technologies can contribute to the aviation industry's climate transition and meet future transportation needs. By modelling future transportation needs and aircraft of different sizes and with various propulsion technologies, researchers have been able to identify the most suitable solutions for different flight destinations and transportation needs. Technologies such as batteries, fuel cells, direct combustion of hydrogen, and Sustainable Aviation Fuels (SAF) have been examined. The project will contribute to different scenarios for the future of aviation, based on two different transportation needs models and how distinct types of aircraft and sizes can contribute to the aviation industry's climate transition. The project's results suggest that there is no single propulsion technology that solves climate change for Swedish domestic aviation or for Scandinavian air transport. Hydrogen has a great potential to contribute, if technology development, hydrogen production and the infrastructure can be developed in time. Battery-powered aircraft can play a role in climate goals but are highly dependent on battery technology development. Battery-driven airplanes are not considered the most decisive technology for green aviation in the envisioned period. In a transition phase, SAF/Biofuel is a main factor in reducing aviation's environmental impact.

Keywords: Sustainable aviation, Norden Europe

1. Introduction

Aviation emissions, though accounting for a seemingly modest 3% of global emissions, play a crucial role in climate change. This significance, often underestimated, stems from the unique conditions under which these emissions occur, particularly their altitude and chemical composition [1]. Concurrently, the transport sector in the European Union, heavily dependent on oil, was responsible for nearly a third of its total carbon emissions in 2018 [2]. The air transport sector's contribution, while numerically small, is increasingly recognized as a factor that cannot be ignored in global warming discussions [3][4]. This recognition has given rise to 'flygskam' or 'flight-shaming' in Europe, especially in Scandinavia, where there is growing consciousness about the environmental impact of flying. In response, Scandinavian governments are leading the charge towards more sustainable practices, setting ambitious goals for the transformation of their air transport sectors. For instance, Norway has declared its intention to electrify all short-haul flights by 2040, and Sweden is targeting carbon neutrality in aviation by 2045, with plans to subsequently achieve a net-negative impact on greenhouse gases [5]. This shift reflects not only a response to the environmental challenge but also an adaptation to the distinctive geographical and demographic realities of the Scandinavian region.

2. Approach

To understand the possibilities and limitations of the Nordic countries, a demand model was developed. The demand model developed is presented in Figure 1. The model, developed by the Swedish Transport Administration, forecasts the transportation needs for Sweden up to 2040. It estimates passenger requirements between all Swedish municipalities, as detailed in a comprehensive report [24]. This model is a key tool for planning, and its specifics can be requested from the Swedish Transport Administration.

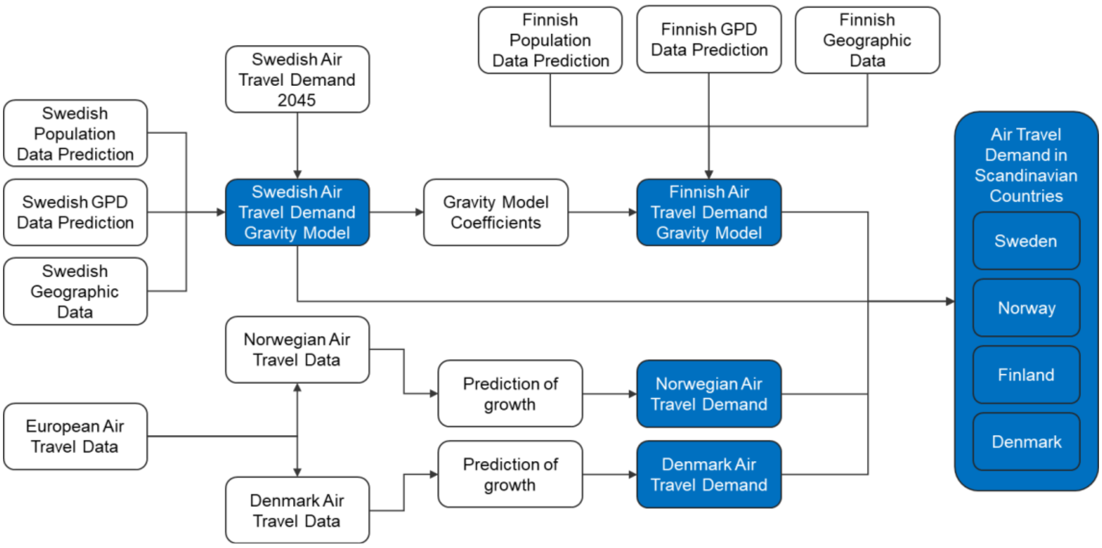

Figure 1 Demand model generation

Notably, the model highlights significant differences in travel patterns across the Nordic countries. In Norway, due to its mountainous terrain and fjords, there is a higher reliance on domestic air travel per capita, as discussed in an Avinor report [26]. This contrasts with Denmark, where domestic flights are surprisingly few. The study explicitly excludes travel data to Greenland.

The report also touches upon the evolving landscape of regional mobility, especially in air transport, between Finland and Sweden. Important work in the Kvarken region, as published in the FAIR project reports [27][28], highlights these developments, although these are more qualitative in nature and do not provide a quantitative model of passenger demand. The Finnish government's studies [29] delve into the prospects of electric aircraft, presenting data and analysis on current low-volume flight routes. Additionally, a Nordregio study [12] investigates the potential benefits of using aircraft for routes under 200 km, in comparison to cars or public transport.

The methodology to develop the passenger needs model involves two approaches: a direct projection from current travel patterns using Eurostat data [25], and a "gravity model". The main process for creating this model is illustrated in Figure 3. The model considers the recovery of air travel post-COVID19, projecting a return to 2019 levels by 2024.

A noteworthy limitation of the current models is their lack of consideration for emerging transport technologies' impact. This aspect was partially addressed in a collaboration with ASDL Georgia Tech [23], and will be discussed in the study's conclusions.

3. Aircraft Modelling

In the project, aircraft have been modelled in two different stages. Initially, rough approximation models were created based on guiding principles. Subsequently, more detailed models with higher resolution were developed, considering the propulsion systems.

In the study, various aircraft sizes were selected, based on current regulations for civil air transport. The aircraft sizes included are distributed in different certification categories from EASA (European Union Aviation Safety Agency) [41]:

- CS-23 and FAR 23 certification rules
  - 9 and 19 passengers
- CS-25 and FAR 25 certification rules
  - 34 and 50 passengers
  - 76 passengers (maximum weight of 86,000 lb. to respect the so-called "scope clause" [42][41])
  - 90 passengers

    - 120 and 150 passengers.

The rules that EASA and FAR have for certifying transport aircraft currently do not cover any of the new propulsion principles presented in this study except for the use of SAF. This study assumes that similar certification rules will be developed to consider the new technologies. It is assumed here that the passenger categories that govern the number of cabin crew onboard the aircraft will remain similar to today and that there will continue to be two certification regimes similar to CS-23 and CS-25. The study also assumes that the USA will maintain a rule similar to the "scope clause", which divides pilots into distinct categories and creates a limitation in aircraft size (maximum weight 86,000lbs) and number of passengers (maximum 76). To comply with today's CS-23 regulatory framework, the aircraft's maximum take-off weight is 8618 kg.

In the study, the aircraft listed above have been modelled with various propulsion principles, with the goal of achieving usable range for each class of aircraft. A simplified principal view of the different propulsion methods considered is shown in Figure 2. The main energy sources and propulsion principles are as follows:

Energy sources:

- Jet fuel (Jet A1), used in the study as a reference
- SAF, where the origin and manufacturing method must be considered to address its climate impact
- Hydrogen
- Batteries
- Propulsion principles:
    - Electric propulsion
    - Batteries or hydrogen (via combustion in fuel cell)
- Direct combustion of hydrogen
- Direct combustion of SAF.

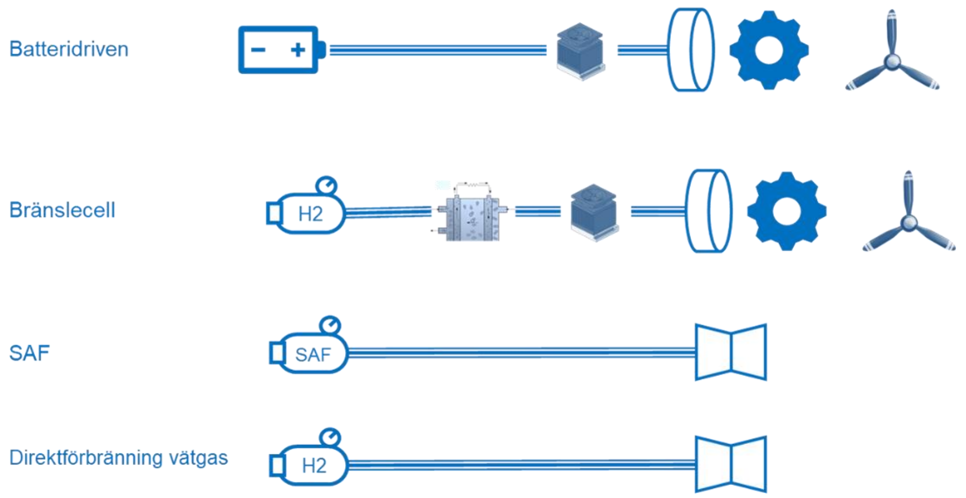

Figure 2 The different propulsion principles, schematic view

In this study, conventional aircraft configurations will be considered. The assumption is that the change in propulsion and energy sources is a sufficiently complex problem for the aviation industry, so the introduction of revolutionary configurations (such as flying wings and distributed propulsion) is not considered. This can be seen as a conservative approach, but the assumption is that if these configurations come, they will be available for a second generation of aircraft with new propulsion. More exotic configurations can be found in the literature. Boeing and Airbus have presented concepts and images of potential future configurations but have indicated that these are still for technology development and should not yet be seen as upcoming commercial products. This aligns with the assumptions of this study.

The objective of these models is to represent aircraft with a higher level of detail that allows for the differentiation between various propulsion technologies. For these models, the Pacelab Suite tool from TXT has been used. This is the same tool used by Saab for early aircraft concept studies. The analysis methods built into Pacelab Suite are based on semi-empirical and statistical methods, calibrated using data and experience from the industry.

To model all aircraft, a so-called standard flight profile for civil aircraft was assumed. It describes in a simplified way how airplanes travel from take-off to destination, considering the need for sufficient energy reserves, either to continue to an alternate airport or to wait before landing near the destination. The flight profile used is shown in Figure 3. Flight reserves depend on the certification base, recommendations, geographic region, and type of operation (VFR, IFR, etc.). The National Business Aviation Association (NBAA) [50] provides a recommendation for extra range to an alternate airport, which is part of the mandatory reserve for instrument flight rule operations. The reserve range is assumed to be 100 NM for turboprop aircraft and 200 NM for jet aircraft. Within the framework of this project, 100 NM has been assumed as the base. Furthermore, all modelled aircraft are assumed to have IFR capability, even though this may be seen as conservative for 9- and 19-passenger aircraft, where VFR conditions might be sufficient for short flights. The choice to assume IFR conditions for the project was made because the Nordic environment can offer varying weather conditions, and regular air traffic should be able to continue daily in all weathers.

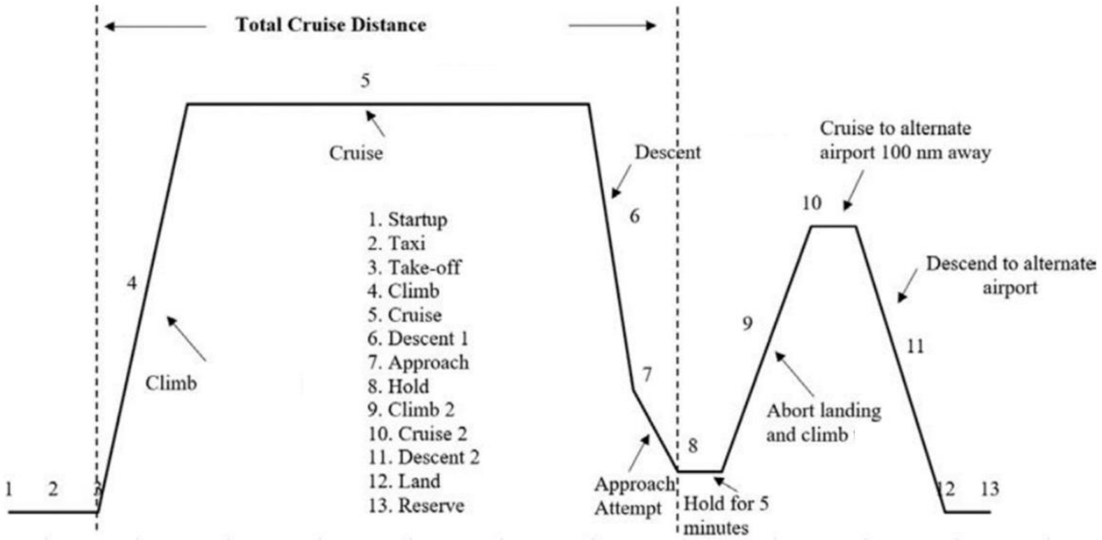

Figure 3 Nominal flight mission for commercial aircraft

The aircraft models developed within the project can represent different propulsion principles, with parameters describing efficiency for electrical systems and fuel efficiency for combustion architectures, as well as the individual weights for the main components in the different propulsion systems. For estimating the weight of the aircraft structure, the standard equations implemented in Pacelab Suite were utilized.

The following assumptions were made in the modelling:

- Electric motor:
  - Efficiency 98%,
  - Power density 5 kW/kg
- Photoelectrochemical cell:
  - Efficiency 98%
  - Power density 2.2 kW/kg
- Cable efficiency 99%
- Power density of fuel cells 1.5 kW/kg
- Power density of cooling systems 2 kW/kg.

For battery-electric propulsion systems, the same assumptions for motor and cable efficiency as for the fuel cell variant were applied. The battery-specific energy density was assumed to be 440Wh/kg for an installed battery, which corresponds to approximately 630Wh/kg at the cell level. This is considered optimistic and is balanced by considering that all electric aircraft also consider 100 NM in reserve to an alternate airport.

For direct hydrogen propulsion, the development of a model for the hydrogen tanks was added, which was developed by Elenius [21] and implemented in Pacelab.

In the project, it was decided not to model hybrid aircraft, as it can be difficult to evaluate different hybrid solutions based on how one chooses to implement the hybridization, and optimization of each such aircraft becomes dependent on the choice of hybridization factor, range, etc. This was a necessary limitation in the study.

The resulting aircraft are listed in Table 1, where aircraft marked EL are electric aircraft with batteries, aircraft marked HD are with direct combustion of hydrogen, HFC stands for hydrogen fuel cells. In the table, references are made either to the aircraft's name (PC12, Beechcraft 1900, Saab 340, and Saab 2000, ATR72, Embraer 190, Airbus A220 and A320), or to the authors of publications from which the aircraft model comes. For all aircraft based on biofuel (SAF), the same range as the original current aircraft is assumed. Note that no aircraft from ongoing development projects have been included in this study.

Table 1Various aircraft concepts, modelled and from published sources, EL, HD, and HFC have been modelled, others come from available publications [51][52][53][54][55][56][57] [22][23][24][25][26][27][28] or values from type certificates

	9 passenger				19 passenger				34 passenger				50 passenger			
	Name	Range [NM]	Pax	MTOW [lbs]	Name	Range [NM]	Pax	MTOW [lbs]	Name	Range [NM]	Pax	MTOW [lbs]	Name	Range [NM]	Pax	MTOW [lbs]
Jet A1	PC 12	750	9	10450	1900 D	440	19	17120	S340	475	32	28500	S2000	1170	50	50700
SAF	PC12	750	9	10450	1900 D	440	19	17120	S340	~475	32	28500	S2000	1170	50	50700
Hydrogen													HD50	1250	50	39743
Fuel Cell	HFC9	215	9	14167	HFC19	250	19	15364	HFC34	266	34	46850				
Battery	EL9	140	9		Staack	120	19	19000	EL34	150	32	32000				
	76 passenger				**90 passenger**				**120 passenger**				**150 passenger**			
	Name	**Range [NM]**	**Pax**	**MTOW [lbs]**	**Name**	**Range [NM]**	**Pax**	**MTOW [lbs]**	**Name**	**Range [NM]**	**Pax**	**MTOW [lbs]**	**Name**	**Range [NM]**	**Pax**	**MTOW [lbs]**
Jet A1	ATR72	830	76	50700	E190	2450	90	114200	A220	3450	120	139000	A319	1170	150	166000
SAF	ATR72	~830	76	50700	E190	2450	90	114200	A220	3450	120	139000	A319	1170	150	166000
Hydrogen	HD76	683	76	46760	HD90	600	90	87929	HD120	379	120	118850	Scholtz	1500	150	156340
	HD76S	1081	76	49600	HD90S	1090	90	92843	HD120S	880	120	123600				
Fuel Cell	Juschus	830	76	85700												

4. Fleet Replacement

The study aims to explore how fossil-free domestic air travel can be achieved in Sweden and the Nordic countries by 2045. This implies that the aircraft fleet must be fossil-free by 2045. In the aviation industry, there are several key factors affecting this:

- Development of new fossil-free aircraft
- Replacement of the existing aircraft fleet with new planes
- Both factors require a certain time to be accomplished.

Historical data illustrated in Figure 4 shows that, assuming known technology and certification base, the development time for a modern aircraft can be considered between 5 and 7 years from the start of a program to the first delivery.

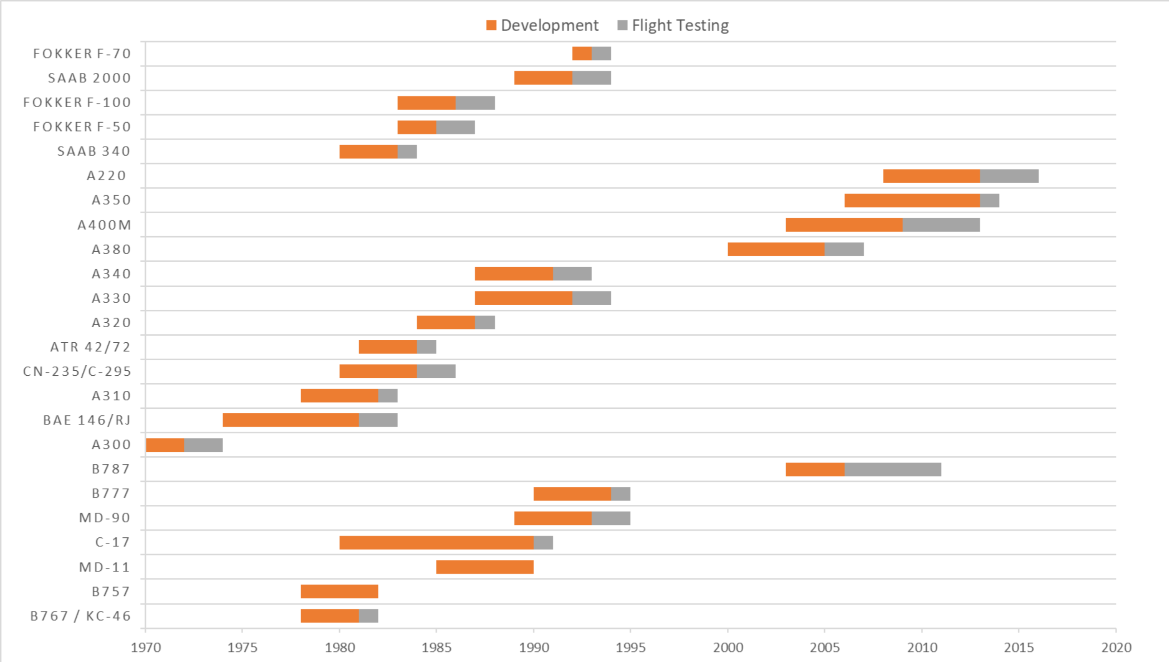

Figure 4 Development times of civil aircraft within the CS-25 category, from program start to first delivery

In summary, if an aircraft is to be in service by 2030, its development should be based on technology that is already mature today. Technology that will be mature by 2030 can be expected to be found in aircraft entering service around 2035–37. In addition to this, the ramp-up of production, economic conditions, and available regulations and certification bases must also be considered.

In this project, no own model for turnover of the aircraft fleet has been developed. Instead, the model from Eurocontrol [15] as shown in Figure 5 has been assumed. The goal is to demonstrate that it takes time to replace an entire aircraft fleet. This can, however, be influenced by many distinct factors such as political incentives and policy, economic controls, and more. Within the scope of the project, no consideration has been given to the turnover of the aircraft fleet, but it has only been noted that it will have a major impact and that the necessary technologies should be mature by no later than 2035, if conversion is to begin on time.

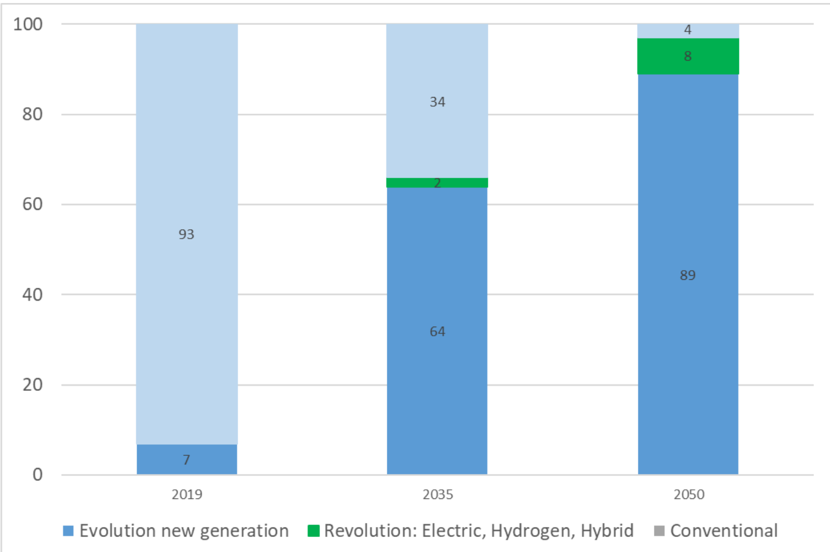

Figure 5 Fleet renewal of the aircraft fleet based on Eurocontrol [15]

As a limitation within the project, it has been chosen to explore whether climate-neutral domestic air transport in Sweden and the Nordic countries could be achieved based on the following assumptions:

- The aircraft studied in this project are assumed to be introduced in suitable time so that the entire Nordic aircraft fleet is replaced by 2045
- All technology considered is assumed to be fully mature by 2028–2030 so that new aircraft can replace the existing fleet

- It takes 5 to 7 years to develop a new aircraft based on known technology.
- This limits the design freedom of aircraft concepts and puts into perspective the challenges of technology and product development within the aviation industry.
- In the project, three main tracks are assumed:
    - Biofuel and SAF are the solutions that can be introduced at a faster pace, this will primarily depend on the production possibilities for biofuel.
    - The introduction of battery-powered smaller aircraft can be carried out from 2030, but the range will be limited. Fuel cells on smaller aircraft can follow battery-powered aircraft.
    - Introduction of aircraft with hydrogen combustion can take place around 2035.

No detailed assumptions about how fast the distinct types of aircraft can be delivered have been made. As an example, Airbus aims to achieve a production rate of 75 A320s per month from 2025. This is considered extremely high and cannot be seen as a guideline to produce new aircraft with new technology, as this has been achieved after a long ramp-up in production over many years.

5. Aircraft Allocation

Passenger demand models describe daily passenger needs on each route. The goal of the allocation is to investigate which types of aircraft can meet this demand while minimizing environmental impact. The reference for aircraft allocation is to assume that all flights are conducted with aircraft powered by Sustainable Aviation Fuel (SAF). To this end, aircraft are selected so that the number of departures on each route is minimized, i.e., the largest possible aircraft are chosen, however, with the consideration that the minimum allowed cabin factor must be 65%. Thereafter, the goal is to replace as many SAF flights as possible with more environmentally friendly propulsion. The aircraft that can be utilized are described in Table 1.

The logic for the allocation is based on the following principles:

- On all flights, the selected aircraft must have sufficient range so that reserve requirements are met.
- A maximum of 15 flights per day can be imposed on the same route (i.e., three two-hour slots per day with departures every 30 minutes).
- Redistribute battery-electric aircraft instead of SAF-powered aircraft on as many routes as possible, with range as the limiting factor.
- On the remaining lines still operated by SAF aircraft, redistribute aircraft with hydrogen fuel cells with regard to range.
- On the finally remaining routes still operated by SAF aircraft, redistribute aircraft with direct hydrogen combustion with regard to range.

Some observations can be made:

- In all cases, a minimum cabin factor of 65% was required, knowing that such a low occupancy rate would require state subsidies to be commercially viable.
- The maximum aircraft size corresponds to an Airbus A321 aircraft with a capacity of 180 passengers. Analysis of passenger data shows that an even larger aircraft could be suitable on certain routes in Norway where the daily passenger volume is extremely high.
- All routes under 150 km were excluded from being operated by aircraft if there are train or road connections, as it was assumed that at such short distances, other modes of transport would be more realistic. However, note that this was not done for Norway, or flights to islands, where even shorter flights might be reasonable to travel over fjords or geographical obstacles.
- The number of flights per day is based on wanting a minimum market volume for air connections to be practically viable. This leads to a minimum of 4 trips (i.e., 2 round trips) per origin-destination pair being considered a minimum. The other thing to consider is that flight departures are not evenly distributed throughout the day, which is illustrated in principle in Figure 6. This leads to the number of departures per day between two airports being limited, as indicated above.

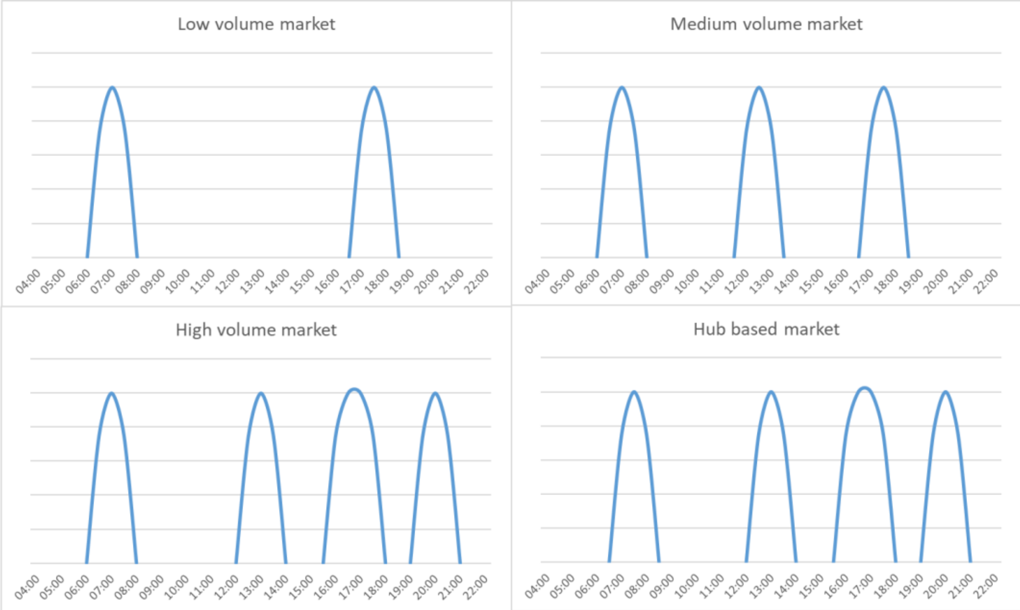

Figure 6 Daily flight times for different markets, adapted from [36]

Another assumption for route allocation is that there will be priority hours during the day, corresponding to a high-volume market. In this case, the total number of trips is limited to a maximum of 16 round trips on a route or 32 flights. This can be compared with the Oslo-Bergen route where there are between 14 and 25 round-trip flights per day. The other assumption is that short routes will often be characterized by passengers who commute for the day. Hence, the market picture is characterized by departures concentrated in the morning and evening, which also limits how many flights it is reasonable to plan per day.

Note that the study did not intend to create timetables but instead tried to analyse the distribution at a higher level of different aircraft types on the various routes. Within the project's framework, no considerations were made to create an operational airline network with possible hubs or economic analyses. In this study, the results were based solely on meeting a certain demand to create an initial understanding of the opportunities offered by environmentally friendly concept aircraft as described in Figure 7.

6. Results

Results for each country and for Scandinavia as a whole are presented based on the following scenarios being studied:

- Scenario 1 - All flights are operated with SAF-powered aircraft except for routes that can be operated with battery-electric aircraft.
- Scenario 2 - As Scenario 1 except routes which can be flown with hydrogen fuel cell-powered aircraft replace SAF-powered aircraft.
- Scenario 3 – Most optimistic, where all flight routes are operated with the aircraft that have the lowest environmental impact according to Figure 7.

	CO_2	NO_x	Water vapor	Contrails, cirrus	Climate impact reduction potential
SAF	0% / -80%	0%	0%	-10-40%	-30-60%
Hydrogen Direct combustion	-100%	-50-80%	+150%	-30-50%	-50-75%
Hydrogen Fuel Cell	-100%	-100%	+150%	-60-80%	-75-90%
Battery	-100%	-100%	-100%	-100%	-100%

Figure 7 Environmental impact

Based on the two need models described earlier, one can calculate the total number of routes that each model contains. As previously explained, a requirement has been set for a minimum number of passengers per route and day for aircraft to be allocated to a route, leading to filtering according to Table 2.

Table 2 passenger demand for the three countries before and after imposing restrictions for minimum number of passengers and minimum travel distance based on need model 1

	Sweden		Finland		Norway	
	Daily Pax Demand	Nr. of Flights	Daily Pax Demand	Nr. of Flights	Daily Pax Demand	Nr. of Flights
On all routes	9541.6	820	15778	351	89938	101
On routes with more than 24.6 pax/day	7699.7	46	14401	101	89938	101
On routes over 150 km	7699.7	46	13636	87	n/a	n/a

6.1 Swedish Perspective

There is a relatively significant difference between the different demand models (see figures for respective scenarios). In the demand model based on the gravity model, 820 routes are represented. By requiring a minimum number of passengers of 24.6 passengers/day (i.e., 2 flights per day, with the smallest aircraft with the lowest permitted cabin factor), this is reduced to 46 routes. Interestingly, this drastic reduction only decreased the total passenger demand by 15%. The cumulative diagram for passengers per kilometre presented in Figure 8 shows that a few routes account for a significant part of all travel. There is, however, a difference between the journeys in the two models, where the dominant journeys do not exactly match between the models. The total daily volume of travellers is, however, similar.

In BM 1, the 3 largest passenger routes represent about 38% of all passenger volume. These 3 routes are Stockholm-Gothenburg, Stockholm-Malmö, and Stockholm-Luleå, where Stockholm-Gothenburg and Stockholm-Malmö account for about 27% of all domestic flights.

In BM 2, instead, the 3 largest routes represent about 40% of all passenger volume. These routes are Stockholm-Gothenburg, Stockholm-Malmö, and Stockholm-Umeå, where Stockholm-Gothenburg and Stockholm-Malmö account for about 33% of all air passengers in Sweden.

Since train infrastructure exists on these routes, and the travel time is about 3 and 4 hours respectively, it is possible that air travel could at least partly be replaced with better use of trains. Many flights are between 350 and 600 km long, which corresponds to routes where there is a more considerable time saving compared to alternative modes of transport. In BM 2, there are significantly more flights at distances 600 to 1100 km than in BM 1. Most of these flights represent a low passenger volume, except for two routes in BM1 not found in BM 2.

Both need models have a strong 'south-north focus', and it is important to state that none of these models seem to capture the need for travel between cities in Norrland.

Scenario 1

In Scenario 1, the modelled passenger needs are examined using electric aircraft. Regardless of the need model, it can be stated that battery-powered aircraft can only represent a small share of the cumulative travel, about 10%. In BH 1, it can be observed that electric aircraft (with battery) capture the short trips with low passenger volume, requiring aircraft with up to 34 passengers. In BM, comparable results are observed. In BM 1, electric aircraft use is limited by range and passenger capacity. For BM 2, it can be stated that there would be a need for smaller aircraft, but the range limitation of electric aircraft becomes the limiting factor.

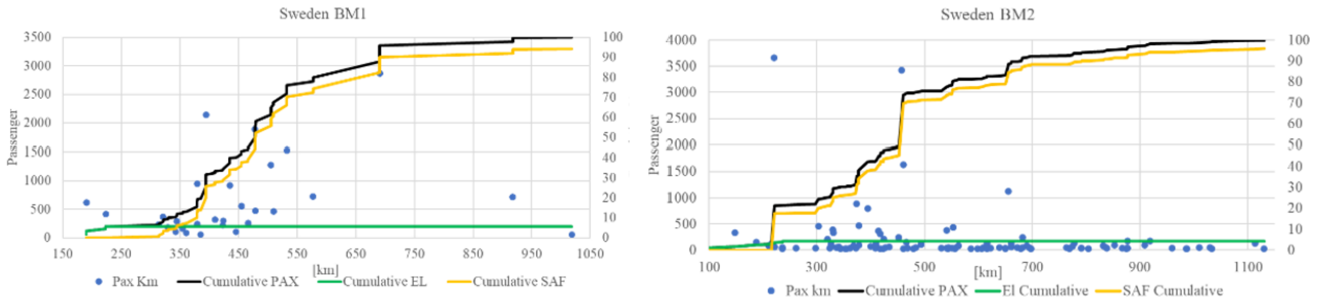

Figure 8 Daily flight needs with passengers per kilometre and the cumulative % of passengers per propulsion technology for Scenario 1 in Sweden

Table 3 summarizes the daily flights per aircraft type and size. Note that the large volumes of passengers on some of the routes lead to aircraft in the 220-passenger class dominating BM1, while in BM2 a greater variation can be observed with several flights with fewer passengers, leading to a higher utilization rate of airports.

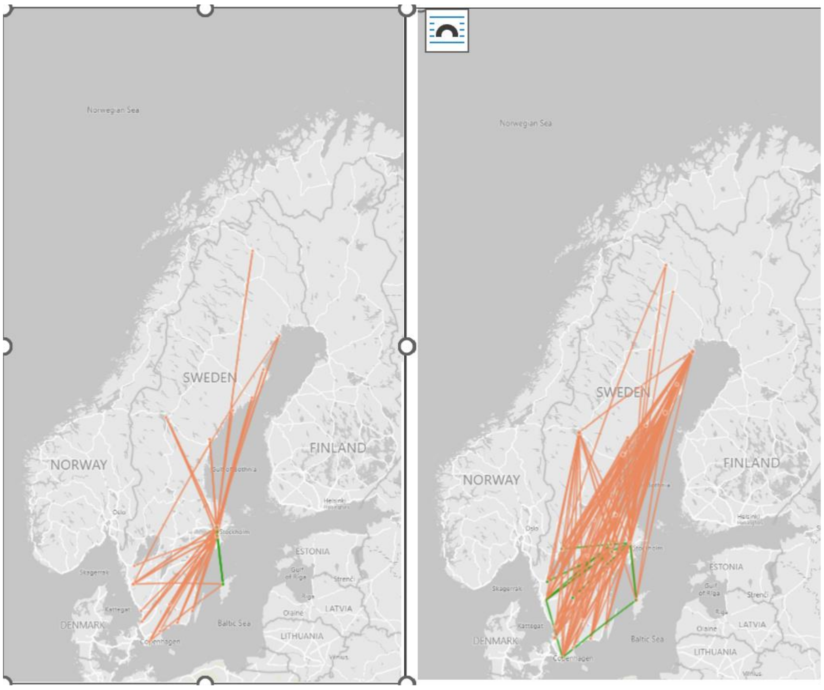

Figure 9 Map of daily routes within Scenario 1, need model 1 on the left and model 2 on the right

In Scenario 1, a few routes are taken up by electrically driven aircraft, which is clearly seen in Figure 9 where the green-marked routes represent the flights operated by this type of aircraft. These routes are found only in southern Sweden. Note that for the Stockholm-Visby route, there is still traffic between both Bromma-Visby and Arlanda-Visby, hence the high number of daily flights with aircraft in the 34-passenger class. Note that if Bromma airport were not included in the need model, the allocation algorithm would have chosen to use SAF-powered aircraft instead, to try to minimize the number of departures per day and route. Both models show that there is a small proportion of routes operated by electric aircraft based on the assumptions made in the project. The biggest limitation is the range and number of passengers.

Table 3 Daily flights per propulsion technology and aircraft size, scenario 1 for Sweden

Daily Flight BM1				Daily Flight BM2			
Pax	EL	SAF	Total	PAX	EL	SAF	Total
9		8	8	9	4	134	138
34	68	2	70	19	8	42	50
50		2	2	34	24	30	54
76		4	4	50		16	16
120		8	8	76		8	8
150		26	26	90		10	10
186		12	12	120		4	4
220		150	150	150		14	14
Total	68	212	280	186		2	2
				220		70	70
				Total	36	330	366

Scenario 2

In Scenario 2, hydrogen fuel cell-powered aircraft are added. This leads to a substantial proportion of all flight routes being allocated to this type of aircraft, which is clearly seen in Figure 10. The cumulative proportion of passengers allocated to fuel cell-powered aircraft is about 60% for BM1, and about 50% for BM2.

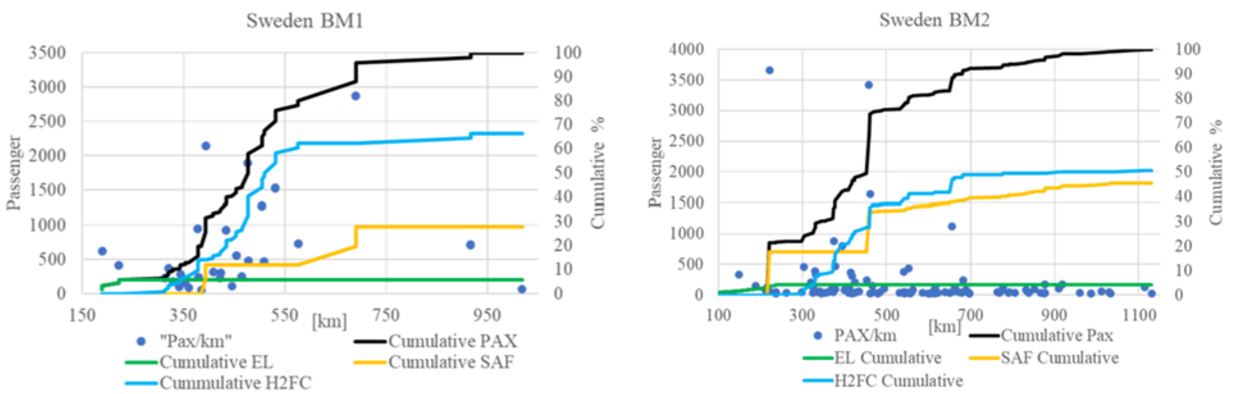

Figure 10 Daily flight needs with passengers per kilometer and the cumulative % of passengers per propulsion technology for scenario 2 in Sweden

In the needed models, it is primarily fuel cell aircraft with a capacity of up to 76 passengers that are distributed to the various routes. For BM 2, there is greater variation. The range of fuel cell aircraft has good potential even for aircraft with smaller passenger capacity. The market remaining for SAF-powered aircraft is primarily routes with a small number of passengers per day, where aircraft with a capacity of 9 to 34 passengers and with relatively long range are needed (see the map of routes in Figure 11 and the summary in Table 4).

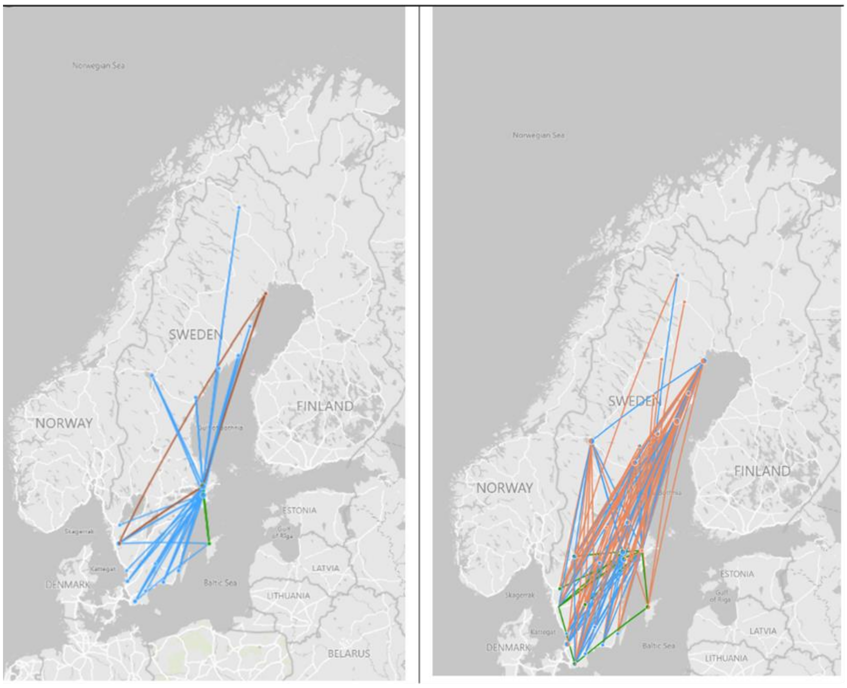

Figure 11 Map of daily routes within Scenario 2, need model 1 on the left and model 2 on the right

The remaining SAF-powered aircraft with higher capacity are allocated to routes with a high number of passengers or routes that are too long even for fuel cell-powered aircraft.

Table 4 Daily flights per propulsion technology and aircraft size, scenario 2 for Sweden

Daily Flight BM1					Daily Flight BM2				
PAX	EL	H2FC	SAF	Total	PAX	EL	H2FC	SAF	Total
9			8	8	9	4	40	94	138
19		6		6	19	8	24	30	62
34	68	26		94	34	24	20	20	64
76		344		344	50			10	10
220			48	48	76		146		146
Total	68	376	56	500	120			4	4
					220			34	34
					Total	36	230	192	458

Scenario 3

In Scenario 3, hydrogen-powered aircraft are introduced, resulting in most flights, measured in cumulative passenger numbers, being allocated to either fuel cell or direct hydrogen-powered planes in both need models. In BM 1, only a few SAF (Sustainable Aviation Fuel) powered aircraft remain, used on routes with few passengers and long range, like Luleå-Göteborg. All other flights for BM1 are covered by alternatives with less environmental impact. BM 2 shows similar trends, though SAF planes are used on more routes with low passenger volume. The difference between BM 1 and BM 2 is clearly shown in the maps in Figure 13 and in the summary in Table 5.

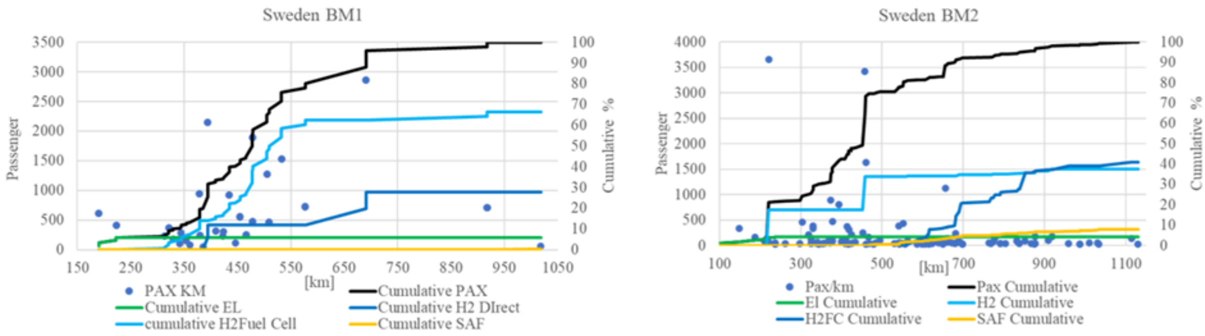

Figure 12 shows the daily flight needs with passengers per kilometer and the cumulative percentage of passengers per propulsion technology for scenario 3 in Sweden. This scenario can be viewed as the most optimistic, where all aircraft operated on domestic routes in Sweden would have been replaced by those with the least possible environmental impact.

Table 5 presents daily flights per propulsion technology and plane size, for scenario 3 in Sweden

Daily Flight BM1						Daily flight BM2					
PAX	**EL**	**H2**	**H2FC**	**SAF**	**Total**	**Pax**	**EL**	**H2**	**H2FC**	**SAF**	**Total**
9				8	**8**	**9**	4		40	94	**138**
19			6		**6**	**19**	8		24	30	**62**
34	68		26		**94**	**34**	24		20	20	**64**
76			344		**344**	**50**		10			**10**
150		72			**72**	**76**			146		**146**
Total	**68**	**72**	**376**	**8**	**524**	**120**		4			**4**
						150		50			**50**
						Total	36	64	230	144	**474**

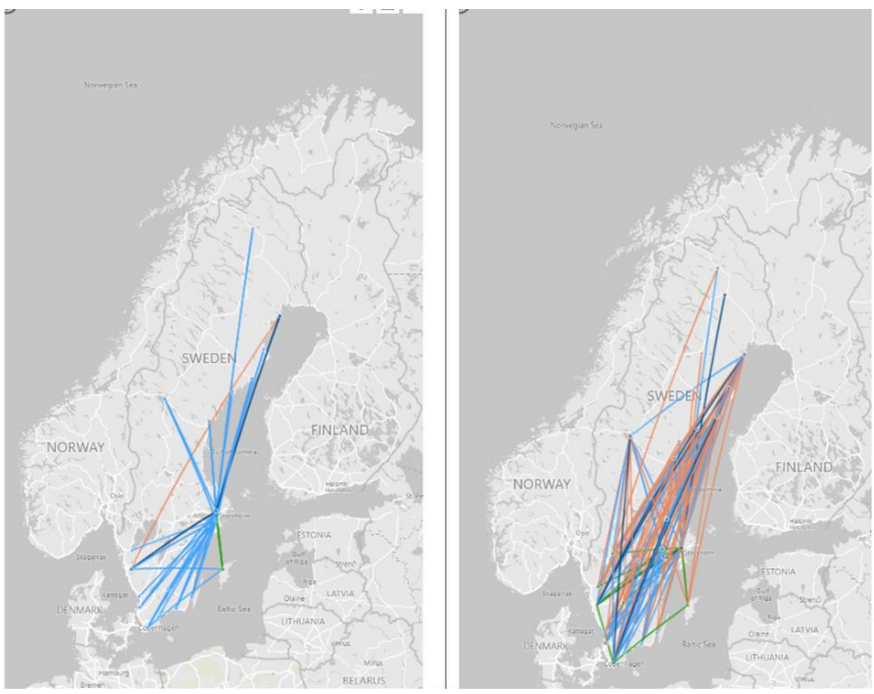

Figure 13 depicts a map of daily routes within Scenario 3, demand model 1 on the left and model 2 on the right

Summary of Findings for Sweden

A clear difference between the two demand models is the larger proportion of smaller aircraft added in BM 2. This can be seen as a direct consequence of considering several direct routes and the sparse Swedish population leading to fewer passenger volumes. The distribution of planes on various routes shows that fuel cell and biofuel planes are the most common propulsion technologies, a direct result of the short range of battery-powered planes. In both models, hydrogen-powered planes are used on routes with longer ranges and higher passenger volumes and are the technology that contributes most to environmental goals. This, however, assumes that infrastructure development and hydrogen production are carried out with renewable energy and that all relevant airports can adapt to hydrogen.

Based on the two different demand models, it is noted that electric planes have limited potential in Sweden, due to range limitations. This is highly dependent on future battery development and the design of reserve requirements. The potential of electric planes is greatest for aircraft in the 34-passenger class. However, within the scope of this study, they do not contribute significantly to the environmental goals set for domestic aviation by 2045.

It is observed that battery-electric planes are assigned a small cumulative passenger volume in Sweden, a consequence of many routes having a range not too long for this type of plane when only direct flights are considered. Hydrogen-powered planes represent the largest type in Sweden, a combination of size and range limitations in the demand model.

Within the scope of the project, creating an efficient flight network to take advantage of different technologies was not considered, as only point-to-point flights are included. This is something that should be considered to see how it would impact the outcome.

Scenario 3 is an optimistic scenario. It is more likely that smaller electric or fuel cell powered planes will be introduced first in combination with a higher use of SAF. Therefore, Scenario 2 is more probable, as it does not assume that all aircraft in service today are replaced with new, environmentally friendly alternatives.

6.2 Finnish Perspective

Just as in the Swedish case, there are significant differences between the two need models in Finland. When considering only routes with at least 24.6 passengers per day (i.e., 2 flights per day with the smallest plane and lowest cabin factor), the number of routes in BM 2 is reduced from 361 to 91. Based on data from the reference year 2019 and including linear annual growth, BM 1 instead contains only 19 routes. In BM 1, the 10 busiest routes represent 47% of all passenger traffic, whereas the top 3 routes alone account for 22% of all passengers. According to BM 2, Finland differs markedly compared to other countries with a much more distributed network, reflecting a more balanced population distribution compared to Sweden or Norway.

In BM 1, it is evident that Helsinki Airport is the hub for all flight routes, as seen in the images of the different scenarios.

Scenario 1

In Scenario 1, SAF and electric planes are considered according to earlier definitions. There is a significant difference between the two demand models, which is clearly illustrated in the route distribution on the map in Figure 14. BM 2 leads to a complex network where electric planes play a significant role.

Table 6 shows daily flights per propulsion technology and aircraft size for Scenario 1 in Finland

BM1				DM2			
PAX	EL	SAF	Total	PAX	EL	SAF	Total
34	34		34	9	50	18	68
150		12	12	19	42	10	52
186		16	16	34	140	12	152
220		50	50	50		8	8
Total	34	78	112	76		4	4
				90		6	6
				120		2	2
				150		12	12
				186		6	6
				220		30	30
				Total	232	108	340

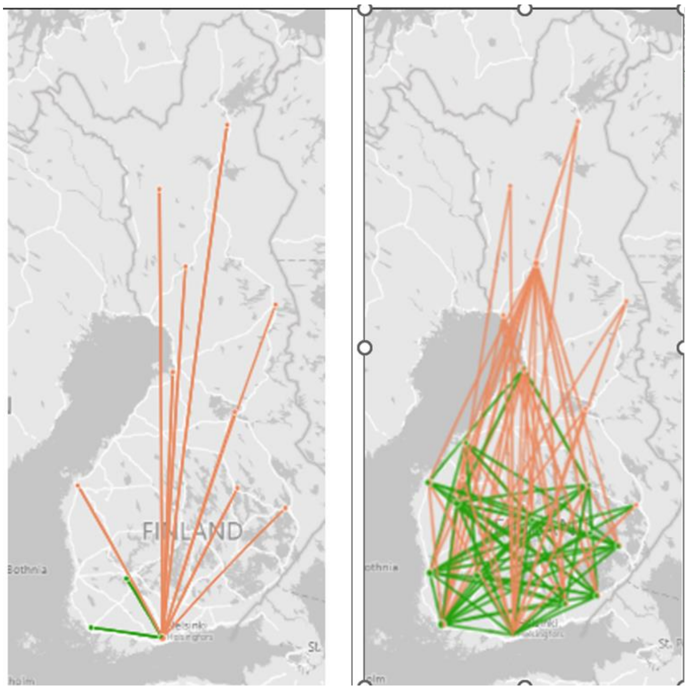

Figure 14 displays a map of daily routes within Scenario 1, with demand model 1 on the left and model 2 on the right

Table 6 presents the total number of allocated flights per aircraft type in the future Finnish scenario. Notably, for BM 2, there is a clear potential for battery-electric planes in Finland, as the more evenly distributed demand favors operations with small planes on shorter routes (Figure 14 displays a map of daily routes within Scenario 1, with demand model 1 on the left and model 2 on the right.). Therefore, there is a distinct potential for an electric plane in the 34-passenger class.

Scenario 2

In Scenario 2, hydrogen fuel cell planes are added, replacing SAF-powered planes on routes where possible. In both demand models, fuel cell planes play a significant role and are successfully introduced on many of the routes previously flown by SAF planes, as illustrated in Figure 15.

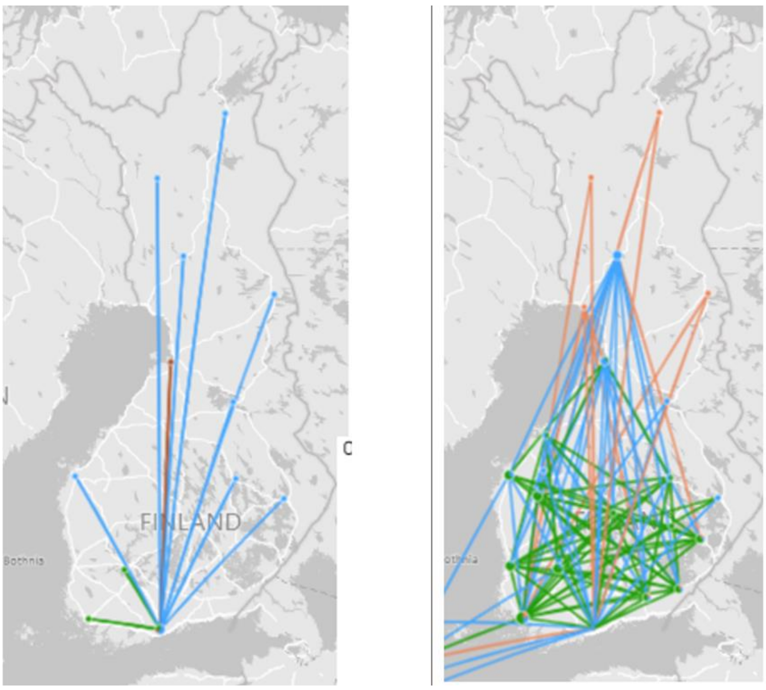

Figure 15 shows a map of daily routes within Scenario 2, with demand model 1 on the left and model 2 on the right

In BM 1, only one route with SAF planes remains, between Helsinki-Oulu, which is a route with high passenger demand. For BM 2, it is primarily routes with long range and low passenger numbers that remain, which is clearly seen in the summary of daily flights in Finland in Table 7.

Table 7 lists daily flights per propulsion type and size for Scenario 2 in Finland

BM1				
PAX	EL	H2FC	SAF	Total
34	34			34
76		116		116
220			24	24
Total	34	116	24	174

BM2				
PAX	EL	H2FC	SAF	Total
9	50	6	12	68
19	42	4	6	52
34	140	24	4	168
50			6	6
76		128		128
Total	232	162	28	422

Scenario 3

In Scenario 3, SAF planes are replaced with planes powered by direct combustion of hydrogen on possible routes. For BM 1, this results in SAF planes being replaced on all routes, illustrated in Figure 16.

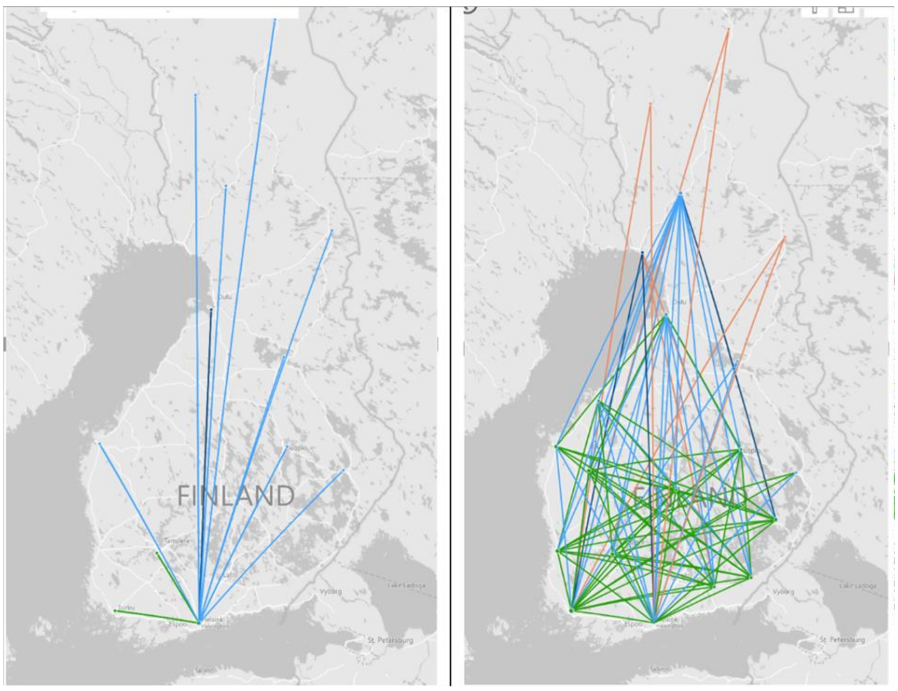

Figure 16 illustrates a map of daily routes within Scenario 3, with demand model 1 on the left and model 2 on the right

For BM 2, SAF-powered planes remain mainly on routes where planes with a capacity between 9 and 34 passengers would operate and where fuel cell and battery-powered planes do not have sufficient range, illustrated in Figure 16. The hydrogen-powered planes added in BM 2 are primarily because no 50-passenger hydrogen fuel cell plane is included in the study, see Table 1.

Table 8 details daily flights per propulsion type and size for Scenario 3 in Finland

BM1					BM2					
Pax	EL	H2	H2FC	Total	PAX	EL	H2	H2FC	SAF	Total
34	34			34	9	50		6	12	68
76			116	116	19	42		4	6	52
150		36		36	34	140		24	4	168
Total	34	36	116	186	50		6			6
					76			128		128
					Total	232	6	162	22	422

Summary of Findings for Finland

In both demand models, fuel cell aircraft have great potential and could thus make a significant contribution to achieving environmentally friendly domestic aviation. It is noted that the cumulative passenger volume flown with battery-electric aircraft represents just over 20% of the total demand and is based on trips under 300 km. Normally, this would be a market that could face competition from road and rail transport if ticket prices and time savings were considered.

Hydrogen-powered aircraft account for most of the routes, with about 70% of all passengers. In BM 2, smaller electric planes could make a significant contribution towards environmentally friendly aviation. Based on range and passenger capacity requirements, primarily a 34-passenger class aircraft fits the bill. According to the study's assumptions, Finland has a small spread in aircraft sizes compared to Sweden. A crucial factor for Finland's domestic aviation is its reliance on a 76-passenger class aircraft in both demand models. As for Sweden, SAF is considered a good transitional solution, but in Finland's case, there is a greater potential to become independent of SAF if fuel cell development progresses at the right pace and if the need can be met with hydrogen production and availability.

6.3 Norwegian Perspective

Norway already has a well-developed aviation network today, and the same network is included in both demand models. Most of the passenger demand is concentrated on a few routes around 400 km long. The 10 busiest routes out of a total of 101 represent 72% of all passengers in Norway, and the top three routes account for 39% of the total volume, these are Oslo-Bergen, Oslo-Trondheim, and Oslo-Stavanger.

Scenario 1

Scenario 1 leads to shorter routes along the coast being replaced by many electric planes, in the 19- and 34-passenger class. Despite the high number of battery-electric planes, only about 10% of the total passenger volume is covered by these smaller aircraft, illustrated in Figure 17.

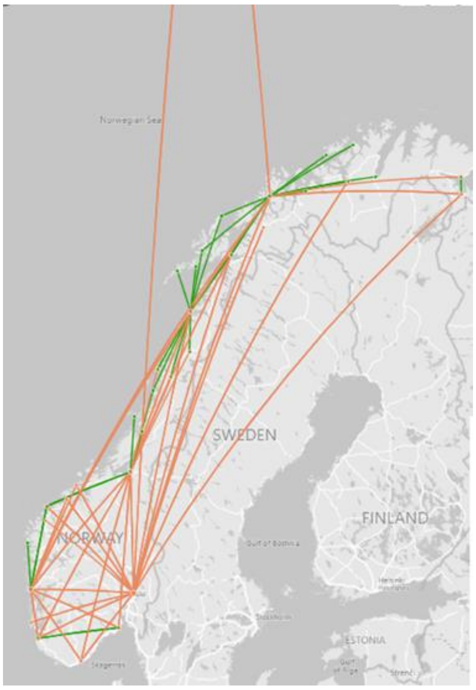

Figure 17 Map of daily routes within Scenario 1

The map of routes in Norway clearly shows that the shorter routes along the coast are well-suited for battery-powered aircraft. The summary in Table 9 clearly shows that, according to the assumed demand model, electric planes represent only a small part of daily domestic flights.

Table 9 Daily flights per propulsion type and size for Scenario 1 in Norway

PAX	EL	SAF	Total
19	46		46
34	150		150
50		6	6
76		6	6
90		14	14
120		10	10
150		14	14
186		12	12
220		358	358
Total	196	420	616

Scenario 2

When introducing fuel cell planes into the demand model, a large part of the routes operated with SAF-powered planes are replaced. The routes that remain with SAF have not been replaced for two distinct reasons:

- Limited range of hydrogen fuel cell aircraft
- Capacity limitations of battery-powered and hydrogen fuel cell aircraft.

This is summarized in Table 10.

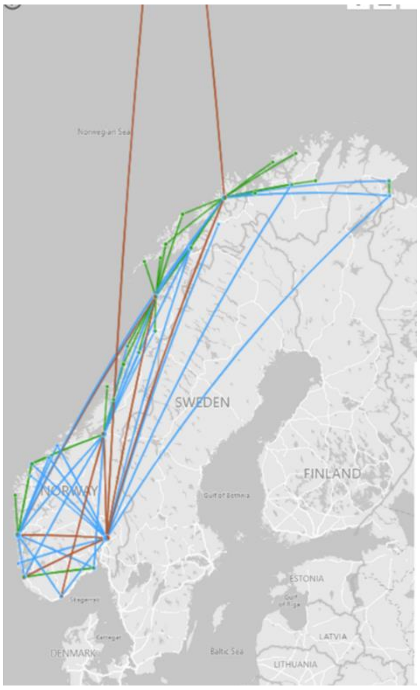

Figure 18 Map of daily routes within Scenario 2

The route distribution between the different propulsion types is illustrated in the map in Figure 18.

Table 10 Daily flights per propulsion type and size for Scenario 2 in Norway

PAX	EL	H2FC	SAF	Total
19	46			46
34	150	20		170
50			2	2
76		442		442
90			2	2
120			6	6
220			212	212
Total	196	462	222	880

Scenario 3

In addition to the three routes with the highest passenger volume that remain operated with SAF planes, in Scenario 3 all remaining SAF planes are replaced with aircraft using hydrogen turbines. The remaining SAF planes could be replaced by one of the hydrogen alternatives, either fuel cells or direct combustion, if the route distribution were changed or more departures per day than assumed in the study were accepted, this is summarized in Table 11 and illustrated in Figure 19.

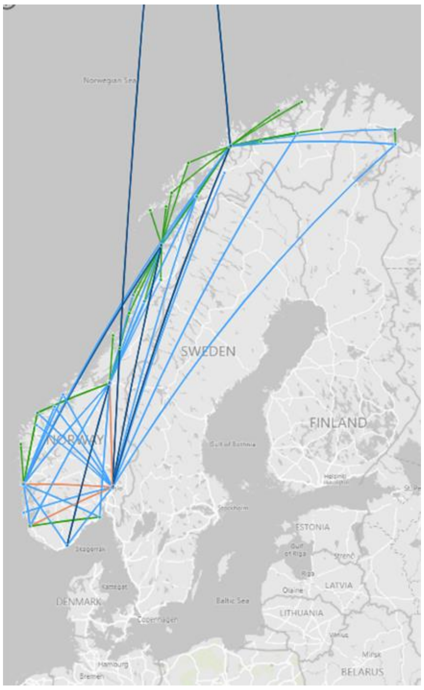

Figure 19 Map of daily routes within Scenario 3 for Norway

Table 11 Daily repartition Scenario 3 for Norway

PAX	EL	H2	H2FC	SAF	Total
19	46				46
34	150		20		170
50		2			2
76			442		442
90		10			10
120		6			6
150		78			78
220				152	152
Total	196	96	462	152	906

Summary of Findings for Norway

Norway has a great potential to replace a large part of the routes operated with SAF (Sustainable Aviation Fuel) powered planes with other environmentally friendly alternative propulsion principles. Within the framework of the assumptions made in the project, hydrogen, and hydrogen-powered aircraft (fuel cell and direct combustion) have significant potential to support the environmental transition. As in other countries, battery-powered aircraft have potential, and a 34-passenger aircraft is the dominant size.

It is worth noting that the daily flight routes within the scope of this project can be divided into three main categories:

- Routes operated by battery-powered aircraft, primarily in the 34-passenger class.
- Routes operated by fuel cell aircraft in the 76-passenger class.
- Routes operated by SAF-powered aircraft in the 220-passenger class.

This reflects a demand model with three types of routes: one with a large passenger volume per day; a mid-market route with medium distances and medium passenger volume; and finally, a market with relatively short range and low passenger volume.

Despite the high number of battery-electric aircraft, only about 10% of the total passenger volume is covered by these smaller planes. Battery-powered aircraft will play a minor role in the overall transition but are an important part of smaller routes. SAF-powered planes will be important in the transition phase to more environmentally friendly flight operations. Finally, the study highlights the significant role that hydrogen could play in the environmental transition.

Summary of Results: Sweden and the Nordic Region

Two different passenger demand models for the Scandinavian countries of Sweden, Finland, Norway, and Denmark have been presented. One model is based on passenger data from the reference year 2019, adjusted with a linear growth until the year 2045. An alternative model for Sweden was developed by Trafikverket and served as the basis for deriving gravitational model coefficients, which were then applied to Finland and Sweden.

Four types of aircraft propulsion systems have been studied and applied to various airplanes with varying passenger capacities. These airplanes have been allocated to domestic routes to meet the future passenger demands developed with the aim of trying to minimize emissions and create sustainable domestic air transport in the Nordic countries. For each country, 3 different scenarios have been studied. The starting point for the first scenario is that all flights are made with planes fuelled with SAF (Sustainable Aviation Fuel), and battery-powered planes are introduced on routes that allow it, based on range and passenger capacity. The second scenario builds on Scenario 1, introducing fuel cell planes to replace SAF planes on the remaining routes if possible. The third scenario aims to introduce planes with direct hydrogen combustion instead of remaining SAF planes if there are routes that allow it.

These three scenarios aim to provide a picture of what different technologies can contribute, based on the assumptions made within the project and the planes that have been modelled.

The following conclusions for each country are drawn:

- In Sweden, there are limited opportunities for battery-electric planes due to their limited range. Planes powered by fuel cells have great potential to contribute to the transition of Swedish domestic aviation when technology and infrastructure are available. SAF will play an important role and is necessary to begin the environmental transition.
- The Finnish passenger demand model does not prioritize a few main lines as in Sweden but is more evenly distributed, which favours the introduction of planes with smaller capacity. Battery-electric and hydrogen planes are in good condition and account for most passenger demand.
- Norway already has a more developed domestic air transport today. Due to its characteristics, the Norwegian market offers opportunities for both smaller electric planes and larger hydrogen-powered planes. Even though there are a considerable number of battery-electric planes, they do not represent a larger part of the total passenger volume.
- Denmark's domestic market is small and can benefit from battery-electric planes and fuel cells.

A main conclusion is that there is no single propulsion technology that solves the entire aviation industry's environmental transition on its own. Each individual technology can contribute, although to a greater or lesser extent.

The general trends in the two different demand models are similar. The biggest difference is that the demand model BM 2 considers several routes with smaller passenger volumes, leading to a greater utilization of smaller planes, see Table 12 and Figure 20.

Based on both demand models, it can be concluded that the outcome from Scenario 3 shows that hydrogen propulsion, based on either fuel cells or direct combustion, has a significant role in the environmental transition. It also shows that battery-powered planes have a role to play, but they can only meet a small portion of the total daily passenger demand, about 10% of the total.

Table 12 Compilation of daily routes per airplane size and propulsion for Scandinavia

BM1						BM2					
Pax	EL	H2	H2FC	SAF	Total	Pax	EL	H2	H2FC	SAF	Total
9				8	8	9	64		46	106	216
19	46		18		64	19	86		34	36	156
34	414		58	2	474	34	456		74	26	556
50		4			4	50		20			20
76			1144		1144	76			892		892
90		4			4	90		8			8
120		16			16	120		14			14
150		442			442	150		206			206
220				152	152	220				162	162
Total	460	466	1220	162	2308	Total	606	248	1046	330	2230

It is worth noting that a plane in the 76-passenger class could be used in a considerable proportion of the daily flights in both demand models. Among the studied battery-powered planes, a 34-passenger plane is the most common. Regarding planes with direct hydrogen combustion, the 150-passenger class would contribute the most. Then there remains the need for an SAF-powered plane with a large passenger capacity.

Based on this study, it is difficult to give a credible prediction of how much emissions could be reduced in CO2-equivalent by 2045, as technological development can change and is, as technological development can change and is driven by commercial conditions. The conclusions that can still be drawn are as follows:

- SAF (Sustainable Aviation Fuel) will play a key role in the environmental transition.
- Battery-electric aircraft can play a role, but it is not dominant in terms of the number of transported passengers and is highly dependent on the technological development of batteries.
- Hydrogen has great potential but depends on technological development and the expansion of infrastructure to a greater extent than SAF and battery-powered aircraft.

The total environmental impact of all different propulsion technologies is strongly dependent on the production and distribution of the energy source.

Battery and fuel cell powered aircraft have the least theoretical environmental impact during flight itself.

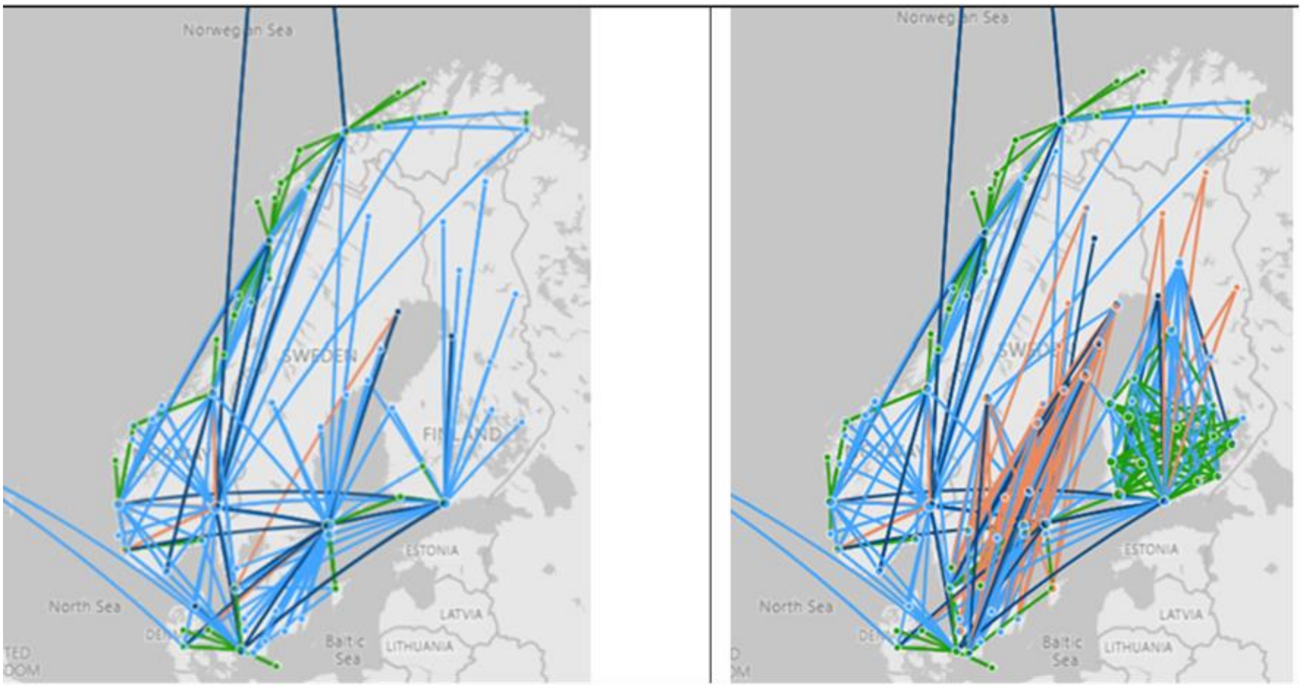

Figure 20 Compilation of Scenario 3 for both demand models for Scandinavia

7. Conclusions

The results presented in this report are highly dependent on the passenger demand models used, but also on the aircraft allocation logic that was developed and the assumed performance of the different aircraft. The lack of accepted and agreed models of future passenger demand for the Scandinavian countries is a limitation. The assumptions underlying the two different models are considered representative but perhaps not entirely complete and can therefore have a significant effect on the obtained results.

From the perspective of the aircraft models, it should be mentioned that the performance of battery technology has a direct and strong impact on range and on the types of aircraft that could be realized. This is common for studies of this kind, but it is worth repeating, as the available battery density is one of the biggest limiting factors, and the results would be significantly affected if unforeseen developments suddenly became available in the future.

In this study, it is assumed that a low cabin factor is commercially acceptable, meaning that domestic flights in the future will still be subsidized by governments to ensure critical connections in the Scandinavian countries. A change in the minimum possible cabin factor would naturally also have a strong impact on the allocation of aircraft on the routes.

The economic viability of the diverse types of aircraft has not been analysed in this study, which is considered to have a major impact on travel patterns and the demand model and should be included in future studies.

In the study, the demand models have only considered air travel. This should be reviewed to get a complete picture including all modes of transport. Within the framework of the collaboration with Georgia Tech, it was explored how reducing travel time can affect the choice of transport, which could lead to increased interest in shorter trips with electric aircraft. On the busiest routes in Sweden, it should be analysed how interaction with trains could be designed.

A key factor not considered in the study is how different energy sources are produced. The study shows that hydrogen can have a significant importance for the transition to environmentally friendly air transport for Swedish domestic flights and for Scandinavia. For this transition to occur, technological development and then a ramp-up of hydrogen production and infrastructure development are needed. Without infrastructure development, the environmental transition will not be able to take place.

SAF is a crucial factor in enabling the environmental transition. Based on the presented scenarios, SAF is the basis for the transition until entirely new technologies become available and can replace current technology and SAF. This is strongly linked to development times and schedules for replacing the aircraft fleet.

Some main conclusions, regardless of the demand model used:

- Battery-powered aircraft are strongly dependent on battery development and primarily on energy density (Wh/kg)
- Battery development will compete with the development of hydrogen propulsion
- Hydrogen is dependent on the development of technology and hydrogen production
- Hydrogen production and distribution are key to the future of hydrogen-powered aircraft
- SAF is considered a necessity to contribute to more environmentally friendly air transport.

There is no single technology that solves all problems on its own:

- The development of new aircraft based on known technology and available certification base takes on average 5 to 7 years. Therefore, the aircraft to be used in 2030 will be based on technologies known today
- Replacing all aircraft takes many years. Therefore, the aircraft fleet in 2045 will be based on technology available long before 2045
- Replacing aircraft cannot be done faster than the production pace and infrastructural development that can be achieved
- Regulations for the different technologies need to be in place to ensure that aircraft developments can be carried out and maintain the same safety standards as today.

From the study, the following aircraft have the greatest impact on a transition:

- Battery-powered aircraft in the 34-passenger class, like the Heart Aerospace concept
- Fuel cell aircraft with 76 passengers
- Hydrogen aircraft with 150 passengers
- SAF aircraft in the 220-passenger class.

Achieving a climate-neutral domestic aviation in Sweden by 2045 is a major challenge, for both demand models with the technical assumptions taken in the project it is difficult to demonstrate that these goals will be fully achieved.

Hybrid solutions have not been addressed but should be considered, as pointed out earlier, a 34-passenger plane has a role to play in the developed scenario, a hybrid solution would open for longer range. However, range is not the only limitation, as the passenger volume on some routes may be too large to be replaced by smaller aircraft.

Since the project does not consider economic factors, adapted flight routes to the technology, timetables, and intramodality, this should be considered in future studies. Further development of the work that has been carried out should be able to help create further understanding and try to quantify different scenarios in terms of equivalent CO2 emissions.

All intended technologies lead to an increased need for electricity production, to meet SAF or hydrogen production and to be able to charge the intended battery-powered aircraft, this should be quantified in future studies.

8. Acknowledgement

The authors would like to acknowledge the Swedish Energy Agency and the Swedish Transport Administration for supporting this research.

9. Contact Author Email Address

Mail to: christopher.jouannet@liu.se (or kristian.amadori@liu.se)

10. 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., et al., “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018”, Atmospheric Environment, Vol. 244, 2021, pp. 117834

[5] Swedish environmental goals, “Utsläpp av växthusgaser till år 2045”, web page https://www.sverigesmiljomal.se/etappmalen/utslapp-av-vaxthusgaser-till-ar-2045/

[6] Swedish environmental goals, official statement, https://www.government.se/articles/2021/03/swedens-climate-policy-framework/

[7] Norway’s Climate Action Plan for 2021–2030; report Meld. St. 13 (2020–2021); https://www.regjeringen.no/contentassets/a78ecf5ad2344fa5ae4a394412ef8975/en-gb/pdfs/stm202020210013000engpdfs.pdf

[8] Finland climate goals, https://ym.fi/en/the-reform-of-the-climate-change-act

[9] Gundelfinger, J., Coto-Millán, P., “Price and demand behaviours in the Scandinavian airline industry following market liberalization,” Journal of Utility Policies, Vol.64, Elsevier Ltd., 2020, https://doi.org/10.1016/j.jup.2020.101052

[10]“Trends and developments in electric vehicle markets,” IAE Global EV Outlook 2021, website https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets

[11]https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

[12]https://nordregio.org

[13]Destination 2050; https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf

[14]The strategic innovation programme InfraSweden2030, webpage https://www.vinnova.se/en/calls-for-proposals/strategic-innovation-programme-infrasweden2030/

[15]Sveriges klimatmål och klimatpolitiska ramverk, https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/sveriges-klimatarbete/sveriges-klimatmal-och-klimatpolitiska-ramverk/

[16]“Waypoint 2050”, IATA report, https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

[17]ICAO 2019 Environmental Report, https://www.icao.int/environmental-protection/Pages/envrep2019.aspx

[18]Destination 2050, “A route to Net Zero European Aviation”, https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf

[19]https://pace.txtgroup.com/products/preliminary-design/pacelab-suite/

[20]Ellénius E., Grahovic D., Qvarnström A., Wennersten J., Åkeson E., ” Utvärdering av prestanda för regionsflygplan med vätgasframdrift” Kandidatarbete 2022, Institutionen för mekanik och maritima vetenskaper, Chalmers tekniska högskola

[21]Garrido Domínguez M. A.,” Swedish Traffic analysis for fossil free air transportation in the year 2045”, Bachelor Thesis, LIU-IEI-TEK-G--22/02170—SE, 2022, Linköping Universitet

[22]Sorrentino R.T., Parello R.C., Delage M., Justin C.Y., Mavris D.N., Jouannet C., Amadori K.,” Zero-Emission regional Aviation in Sweden,” International Council of the Aeronautical Sciences, ICAS 2022 Stockholm Sweden

[23]“Resandeprognos för flygtrafiken 2040 Trafikverkets basprognoser 2020-06-15”, http://trafikverket.diva-portal.org/smash/get/diva2:1443411/FULLTEXT01.pdf

[24]Eurostat, https://ec.europa.eu/eurostat/web/transport/data/database

[25]Avinor, “Aviation in Norway. Sustainability and social benefit,” 4th Report, October 2020

[26]Electrical Aviation 2022, regional prerequisites for electrical Avaviotn, 2022, https://www.kvarken.org/projekt/fair/

[27]Mäenpää A., Kalliomäki H. and Ampuja V, “Potential Impacts of Electric Aviation in the Kvarken Region Stakeholder views in 2020”, April 2021 https://osuva.uwasa.fi/handle/10024/12435

[28]Electric aviation a viable future option in Finland https://www.traficom.fi/sites/default/files/media/file/S%C3%A4hk%C3%B6inen%20lent%C3%A4minen%20Suomessa.pdf

[29]Lundberg T., “Accessibility study for electric aviation,” Nordregio, https://storymaps.arcgis.com/stories/3b35687163744e69a6966b5b9fad976e

[30]The strategic innovation programme InfraSweden2030, webpage https://www.vinnova.se/en/calls-for-proposals/strategic-innovation-programme-infrasweden2030/

[31]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

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

[33]Google Distance Matrix API overview https://developers.google.com/maps/documentation/distance-matrix/overview

[34]Braune R., Frank J., Liss V., “Resandeprognos för flygtrafiken 2040”; Publikationsnummer: 2020:122; ISBN 978-91-7725-653-3

[35]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

[36]https://www.stat.fi/index_en.html

[37]Bråthen S.,Halpern N. andWilliams G., “The Norwegian Air Transport Market in the Future”, Avinor, “Aviation in Norway. Sustainability and social benefit,” 4th Report, October 2020

[38]Solvoll G., Mathisen T. A., Welde M, “Forecasting air traffic demand for major infrastructure changes, Research in Transportation Economics”, Volume 82, 2020, 100873, ISSN 0739-8859, https://doi.org/10.1016/j.retrec.2020.100873

[39]EUROCONTROL Aviation Outlook 2050, Main Report 2022, https://www.eurocontrol.int/sites/default/files/2022-04/eurocontrol-aviation-outlook-2050-report.pdf

[40]EASA certification specifications, https://www.easa.europa.eu/en/document-library/certification-specifications

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

[42]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.

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

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

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

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

[47]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

[48]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

[49]National Business Aviation Association, “NBAA Management Guide,” Washington D.C., 2011

[50]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

[51]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.

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

[53]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.

[54]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

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

[56]Scholtz 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

[57]Madavan N., “A NASA Perspective on Electric Propulsion Technologies for Large Commercial Aircraft”, ESARS-ITEC 2016, Toulouse, France, November 4, 2016