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Towards Zero-Emission in Air Transportation in Scandinavia

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The Scandinavian region mixes several interesting features. Metropolitan and urban areas with relatively high population density coexist next to vast but sparsely populated areas; modern ground infrastructures connect larger cities, but smaller communities are less efficiently served; geographical hinders such as mountains, jagged coast lines, lakes and the Baltic Sea further complicate transportation across the region. Previous work has studied how the emergence of new eco-friendly air vehicles designed for shorter routes could stimulate efficient and profitable regional operations in Sweden, especially if they leverage currently underutilized and paid-for airports. Using a purposely developed demand model, forecasts were created to study the changes in mode choice as a result of new regional flights between underserved airports. The idea was that the introduction of environmentally-friendly aircraft would enable revitalizing new routes. In the present paper, the work has been further expanded to broaden the perspective beyond the Swedish borders, taking into consideration also neighbouring countries. To achieve this, regional air transportation demand models were needed for both Norway and Finland. Then, a future scenario is considered to investigate how different sustainable aircraft solutions impact the domestic air transportation in the Scandinavian countries, comparing both potential and applicability of adopting Sustainable Air Fuel, electric or hydrogen fuelled propulsion systems.

I. Nomenclature

MTOW = Maximum Take-Off Weight
PEC = Photo Electro Chemical cell
SAF = Sustainable Aviation Fuel
SME = Subject Matter Experts
SoS = System of Systems
TRL = Technology Readiness Level

II. Introduction

According to current studies, aviation emissions are only responsible for about 3% of global emissions, whilst the global air travel and transport industry produced an estimated 32.6 billion tons of carbon dioxide emissions from 1940 to 2018 [1]. At the same time, in the EU, the transport sector represented almost one third of total carbon emissions in 2018, mainly because of its dependence on oil [2]. Although the air transport sector is responsible for only a numerically small percentage of the total CO_2 emissions, it has already been documented (see e.g. [3] and [4]) that its impact on global warming cannot be neglected, due to both the altitude at which the emissions are released

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and the composition of the emissions themselves. As partial reaction, among the European population and in Scandinavia in particular, the "flygskam" or "flight-shaming" is spreading in a trend where people are ashamed to fly because of the associated carbon emissions. Scandinavian governments [5][6][7][8] are also driving the transformation, having decided on an aggressive environmental policy to reach quickly sustainability, also in the transport system. For instance, Norway announced that all its short-haul flights would have to be electric by 2040, whereas Sweden has set as a goal to be carbon-neutral by the year 2045, and to then have a net-negative contribution to green-house-gasses from thereafter [5].

Scandinavia is an interesting region as explained by Gundelfinger et al. [16], because the Northern Countries are scarcely populated (see Figure 1), train infrastructure is not as developed as in Continental Europe, there are significant geographical hinders and the climate and vicinity of the Norther Pole makes flying the preferred means of transportation in the northern parts of the Region. The region is also characterized by a high degree of environmental commitment and positive attitude towards new technologies, as can be for instance observed looking at the diffusion of electric vehicles (especially cars) which is growing rapidly [17].

It has been observed [37] that sustainability cannot be reached only pursuing one single solution, but will require balancing of different modes of transportation, taking a broader System-of-Systems (SoS) perspective. Therefore, the interplay different modes of transportation shall not be seen in competition to one another, but as contributing pieces of a complex puzzle. This has partially been observed and promoted by Swedish policy-makers, who for instance have founded a wide range of research projects aimed at driving towards sustainability of the transportation infrastructure within the InfraSweden2030 program [12].

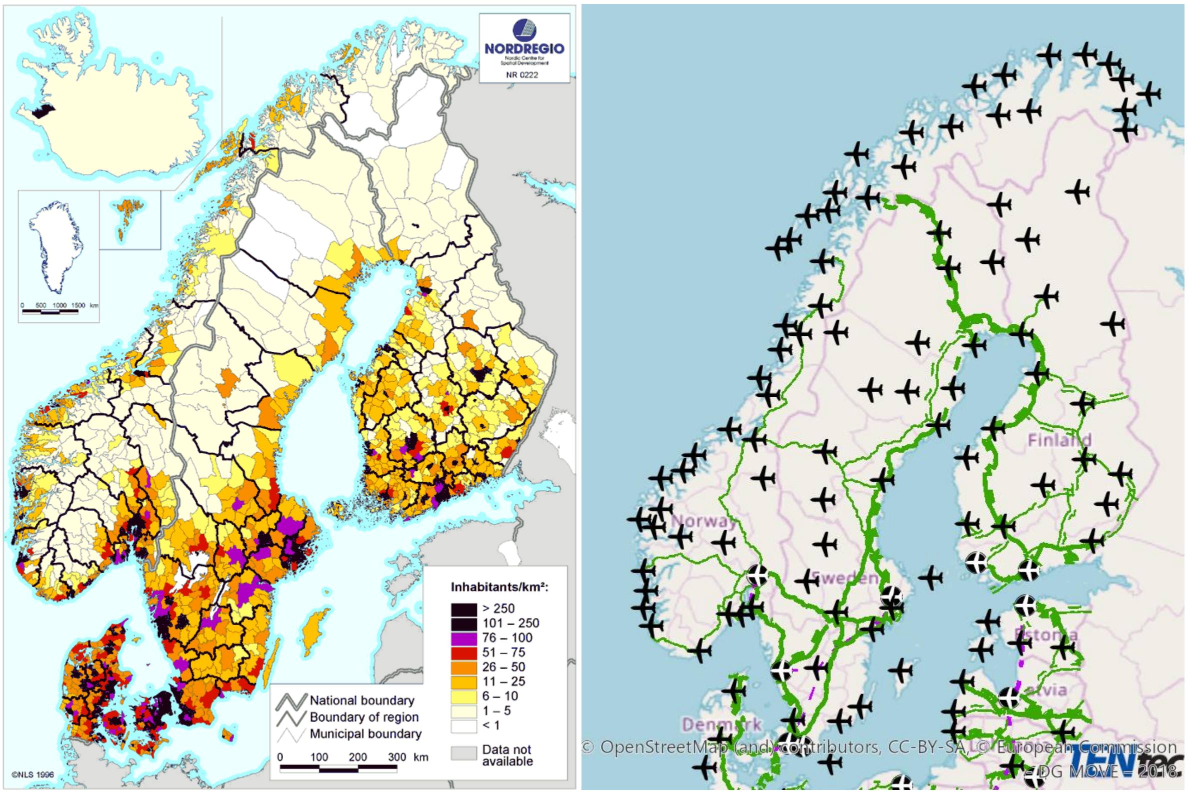


Figure 1 Population density in Scandinavia and rail and airport infrastructure [18][19]

However, in this paper, the focus has been on the regional domestic air transportation in Sweden, Norway and Finland. Although having significant similarities, these countries present also fundamental differences that have a direct impact on transportation patterns and needs. Norway has a mountainous landscape that render terrestrial transportation challenging, a jagged coastline in which fjords becomes geographical hinders and a small population that leaves vast regions very sparsely populated. Transportation data from Eurostat [9] show that domestic air travel passenger volume in Norway is about five times larger than in Sweden and eight times than in Finland. And yet, Finland and Norway have roughly the same population, which is about half of that in Sweden. Additionally, the number of domestic routes served in Norway is significantly larger than in the neighbouring countries, see Figure 9.

The goal of the work presented in this paper was to study the impact, feasibility and potential of alternative notional eco-friendly regional aircraft in the domestic operations in the three countries. The aircraft are designed to be propelled either by Sustainable Aviation Fuel (SAF), or electric batteries or hydrogen (see section IV). To enable the comparison, first future domestic air travel demands for the three countries have been estimated (see section V). Then, in section VI, four scenarios have been studies and compared. The case in which all aircraft are fuelled by SAF is used as baseline and compared to three alternatives, in which mixed aircraft fleets are introduced by adding 1) battery-electric propulsion, 2) hydrogen fuel cells or 3) direct hydrogen combustion propulsion technologies.

III. Summary of Previous Findings

The proposed paper is a further development of two precedent projects by the authors, which can be found in ref. [10] and [11]. The goal of the first one was to build a model enabling decision-makers to assess the effects of their environmental policies on the regional aviation market while accounting for different scenarios, new breakthroughs in technologies, and the competition from other means of transportation. Within the study, a model was created to forecast regional travel demand in Sweden while estimating the corresponding carbon emissions per means of transportation, with a focus on air transportation. The analysis was compiled into a dynamic dashboard to enable what-if, sensitivity analysis. The end-user of this dashboard could select different technologies such as alternative propulsion devices to modify the emissions associated with air travel, as well as policies to influence travel demand. The project entailed four different successive steps:

1. Travel demand modelling will be estimating the demand for travel in the Nordic countries using a conventional 4-steps method. The output of this step will be a mode-specific demand table, illustrating the travel demand for car, buses, trains, and airplanes, for pre-defined city pairs.
2. Fleet allocation will assign a frequency of flights and an aircraft gauge for each market depending on the demand found in the previous step. The authors plan to use airlines' current schedules to estimate the type of aircraft to use. The gauge of aircraft flying between currently underserved city pairs will be estimated using historical airline behaviours.
3. Emissions modelling will compute the carbon emissions associated with each mode of transportation. The environment will need to consider emissions associated with alternative propulsive devices such as hydrogen and electric powertrains.
4. Visualization will be concerned with the implementation of the dashboard. The end-user will be able to modify the results based on selected technologies and policies. The authors chose the bokeh Python library to build this dashboard.

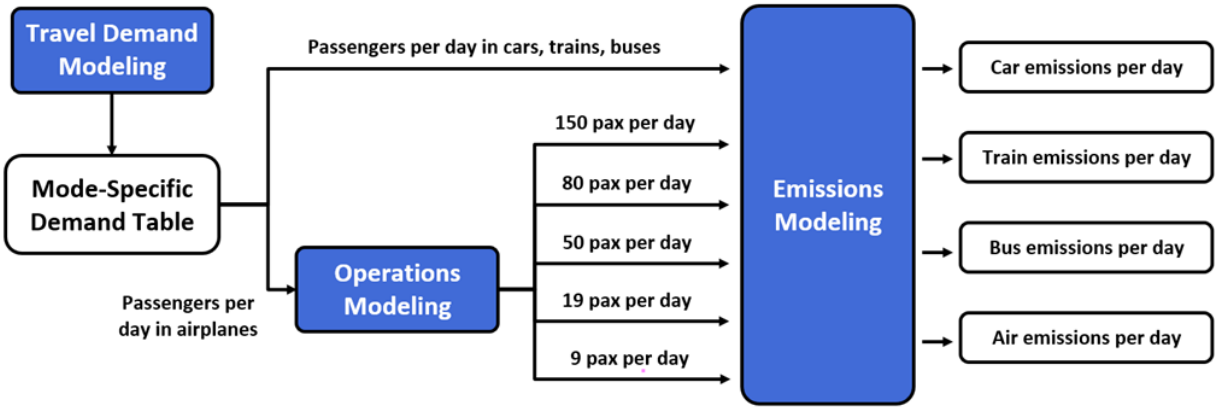


Figure 2 Modelling approach in the study by Sorrentino et al. [10]

The goal of the second project (see [11] for further details) was 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 European perspective. The project investigated the potential and feasibility of new or upgraded aircraft types based on the different technologies mapped from various published roadmaps and national expertise from Swedish aerospace universities and companies. The demand assessment was based on the data made available from

Trafikverket, the Swedish Transport Administration, which represents a prediction of the Swedish transport demand for 2040, divided into four main transportation modes: bus, air transportation, train, and car. This demand model allowed to analyse the forecasted air travelling demands, and compare it with predicted performance for different aircraft types and sizes. It was observed that careful planning is necessary to take maximum advantage of coming technologies that are expected to guarantee diminished emissions, but also that integration with other modes of transportation is important to reach zero-emission goals.

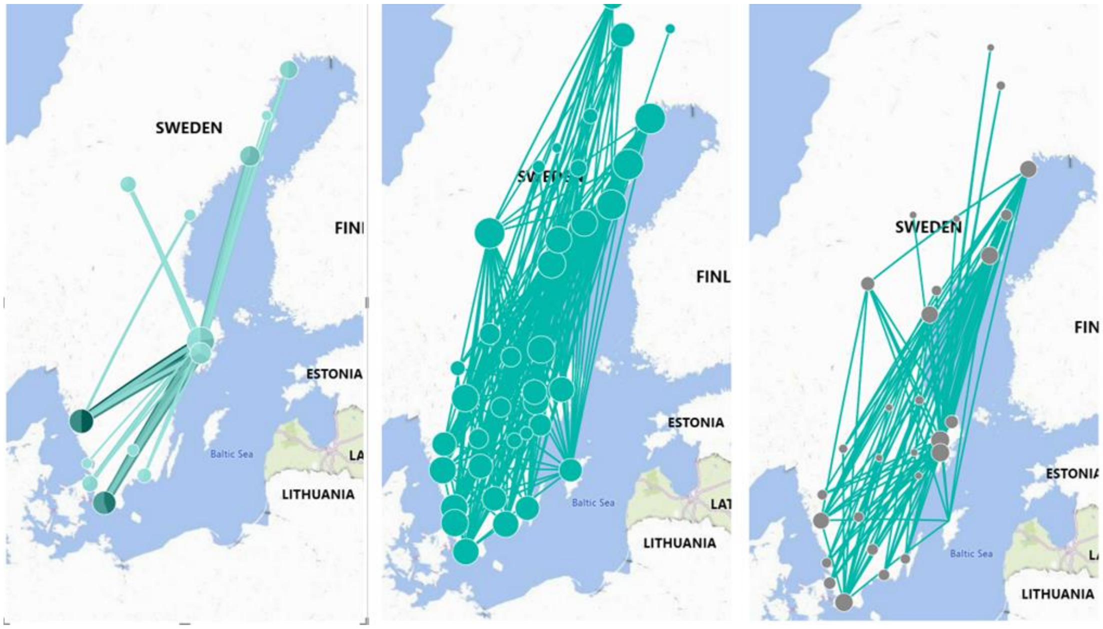


Figure 3 Flight demand in Sweden, represents 70% of all daily passengers (left), all demand for less than 9 passengers (middle), and routes with a demand superior to 9 passengers (right) – as presented in [11]

IV. Aircraft Models

Within the scope for this project, different aircraft have been considered in order to have alternative vehicles that can be chosen for each route, based on needed passenger capacity and distance to be flown. This section provides a brief summary of the different aircraft sizes that have been considered:

1. CS-23 and FAR 23 certification base
    a. 9 and 19 passengers
2. CS-25 and FAR 25 certification base
    a. 34 and 50 passengers
    b. 76 passengers (maximum take of weight of 86,000 lb to respect scope clause [29])
    c. 90 passengers
    d. 120 and 150 passengers.

A notional flight mission is considered to follow a typical commercial flight profile, such as illustrated in **Error! Reference source not found.**. Flight reserves are dependent on the certification base and recommendations. For CS-23, the following applies:

1. VFR: a reserve of 30 or 45 minute applies
2. IFR: a reserve of 30 or 45 minutes in addition to divergence to the alternate airport.

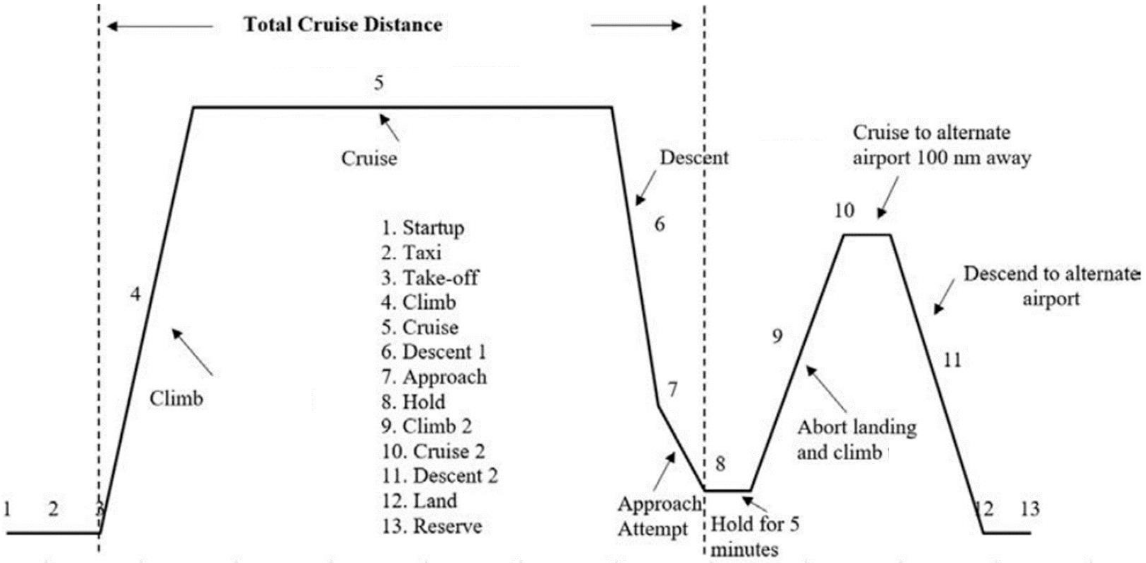


Figure 4 Notional flight mission for commercial aircraft

For each passenger capacity category, different propulsion technologies are being considered to see their applicability and impact in the three countries. The following main propulsion principals and source of energy have been considered:

1. Sustainable Aviation Fuels (SAF), which is the baseline case for the study
2. Hydrogen
   a. Direct combustion
   b. Fuel cell
3. Battery-electric.

Aircraft that have not been modelled within the project are taken from other studies, see Table 1 Different aircraft concept modelled and from literature, EL, HD and HFC have been modelled, other come from available publications [22][23][24][25][26][27][28] or values from type certificate.Table 1. Properties of all modelled aircraft have been estimated using the design tool PaceLab APD [20], using off-the-shelf models for aerodynamics and weight estimation, only employing in-house correction factors on some weight equations.

SAF-fuelled aircraft have not been modelled, since data for those aircraft were based on the aircraft type certificate, because in case of SAF it has been assumed that all parameters remain the same as for Jet A1 variants.

For aircraft with hydrogen propulsion, cryogenic liquid hydrogen systems were assumed. The fuel have been modelled taking into account the weight for hydrogen tanks, whereas propulsion adjustments were done by tuning SFC and specific fuel energy.

For hydrogen fuel cell propulsion systems, the following assumptions were used:

1. Electrical motor:
   a. Efficiency 98%,
   b. Power density 5 kW/kg
2. Photo Electro Chemical cell:
   a. Efficiency 98%
   b. Power density 2.2 kW/kg
3. Cable efficiency 99%
4. Fuel cell power density 1.5 kW/kg
5. Cooling system power density 2 kW/kg.

For battery-electrical propulsion systems, the same assumptions were applied for motor and cable efficiency as for the fuel cell case. Battery specific energy density was assumed to be 440Wh/kg at pack level. All electrical aircraft were modelled based on a simplified approached described in [11].

In this paper, the operational range (as defined by the mission profile in Figure 4**)** and the passenger capacity are the two main aircraft parameters used to allocate the different aircraft throughout the various routes to meet the estimated passenger demands.

In Table 1the aircraft labelled EL are electrical aircraft with battery as power source, aircraft labelled HD stands for direct combustion hydrogen, HFC stands for hydrogen fuel cell, the others refers either to the aircraft name (PC12, Beechcraft 1900, Saab 340 and Saab 2000, ATR72, Embraer 190, Airbus A220 and A320), others with names refers to the authors of publications where the aircrafts comes from.

Table 1 Different aircraft concept modelled and from literature, EL, HD and HFC have been modelled, other come from available publications [22][23][24][25][26][27][28] or values from type certificate.

	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	ES50	250	50	50500
	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												
Battery																

V. Passenger Demand Models

As previously depicted in Figure 2, the starting point for the analysis was the travel demand model. The model should describe the needs in the future timeframe assumed for the analysis. The Swedish Transport Administration (Trafikverket) has produced a detailed forecast model of travel demand for the year 2045, available on demand, in which passenger demands for each city pair in Sweden is estimated, for each mode of transportation, the overall data conclusion for that are summarized a report [21]. Unfortunately, no similar projection was available for Norway and Finland. Trying to create a future passenger demand model for those countries is beyond the scope of the present work, so it was decided to adopt the process as described in Figure 5, to allow deriving future air travel demands for each individual nation and for the Scandinavian region as a sum. However, analysing the available historic travel data [9] it was observed that there are fundamental differences that make Norway to stand out. Norway has a mountainous topography and the coastline is characterized by a myriad of fjords, and the importance of air transport and its future development has been detailed in report by Avinor [35]. As a result, terrestrial transportations are less common than in Sweden and Finland, where road and railroad infrastructures are more used. This is reflected in significantly higher passenger volumes in domestic air travel in Norway (five and times higher than in Sweden and Finland respectively) and in a larger number of active routes connecting many more destinations.

For Finland and Sweden several reports describe the opportunities that potential future air transport could offer for regional mobility in between regions across the Scandinavian countries' national borders. Substantial work has been performed in the Kvarken region and findings have been published by Kvarken local authorities in the FAIR project [30],[31]. However, these aspects have not been included in this project, because the available publications do not offer a quantitative passenger demand model, but rather describe qualitatively what could be possible to achieve. Similar studies are also available from the Finnish government, which point out the possibilities that electrical aircraft could offer [32], presenting data and analyses on the current routes with low daily passenger volumes.

For these reasons, a common demand model could not be derived for the three countries, but a different approach was necessary, as shown in Figure 5.

A. Strategy for the Development of Future Passenger Demand Models

The predicted demand model by the Swedish Transport Administration was adopted in this project. Although different modes of transportation have been predicted, for this project only passenger volumes in domestic air travels have been considered. The model is fairly detailed and estimates the travel demand for each municipality pair. Hence, passenger volumes have been aggregated to the nearest active airport, so that the resulting model would describe the travel demand between airports. Since Swedish domestic air travel today is somewhat limited, so-called airport catchment was done assuming instead the availability of a much larger number of airports. The reasoning was that the future availability of sustainable aircraft could re-energize the domestic market and incentive a growth towards destinations that are not served today. A total of 41 airports have been considered in Sweden. This meant that the modelling complexity was reduced, since the dimensionality of the required demand model became much smaller. The assignment of a reasonable metropolitan area around each airport was done distributing each municipality to the nearest airport measured by travel time.

The process depicted in Figure 5 was developed to derive predictions of domestic travel demands in the three northern countries and will be explained in mode details in this section. Section V-B describes how a gravity model was derived and optimized to match the demand model prediction available from the Swedish Transport Authority. The gravity coefficients were then used to obtain a prediction of travel demands for Finland (see section V-C). Finally, section V-D describes how the Norwegian demand model was developed.

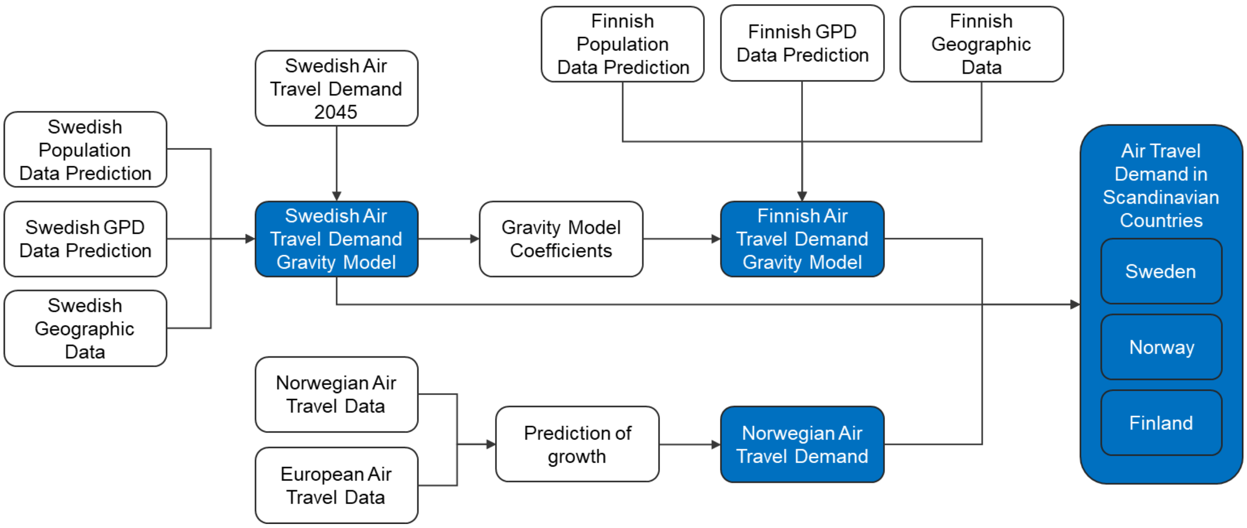


Figure 5 Process to generate air travel demand models for each nation and for Scandinavia

B. Swedish Demand Model

The first step required to approximate the known Swedish air travel demand with a gravity model based on data that could be obtained also for the other nations. Typical example of gravity model for aircraft demand can be found in [13][14][15]. Finally, the gravity model was built in log-linearized form as following:

$$\hat{V}_{ij} = \alpha + \beta_1 G_{ij} + \beta_2 P_{ij} + \beta_3 D_{ij} + \beta_4 U_{ij} + \beta_1 H_{ij} + \beta_1 C_{ij} \tag{1}$$

Table 2 details the meaning of each term in the gravity model. The circumflex sign is used to indicate that the passenger volume is estimated. Although the available demand data was not symmetric (i.e., travel demand from origin A to destination B was not the same as from B to A), it can be observed that the mathematical model (1) is instead symmetric. Hence, before optimizing the weighting coefficients, the reference demand data was folded over its diagonal so that the volume V_{ij} would indeed represent the number of passengers traveling in both directions between origin *i* and destination *j*, so that:

$$\hat{V}_{ij} = V_{ij} + V_{ji} \tag{2}$$

Table 2 Parameters and variables in the gravity model. Since the National statistical data from Statistic Sweden (Statistikmyndigheten SCB) only provide current data, official growth predictions for population and GDP have been applied. Number of hospitals and universities were instead kept constant.

Notation	Functional Form	Data
V_{ij}	$ln(Volume_{ij})$	(Estimated) total number of passengers between airport *i* and *j*
$\square$	Constant term	Parameter
$\square_{\square}$	Coefficient	Weighting coefficient for each log-term
G_{ij}	$ln(GDP_i \; x \; GDP_j)$	Metro catchment area GDP in thousands of SEK
P_{ij}	$ln(POP_i \; x \; POP_j)$	Metro catchment area population in thousands of people
D_{ij}	$ln(D_{ij} \; x \; D_{ij})$	Great circle distance in km between airport *i* and *j*
U_{ij}	$ln(U_i \; x \; U_j)$	U_i represents the number of universities in metro catchment area of airport *i*
H_{ij}	$ln(H_i \; x \; H_j)$	H_i represents the number of hospitals in metro catchment area of airport *i*
C_{ij}	$ln(C_i \; x \; C_j)$	C_i is equal to 1 if metro catchment area *i* contains the nation capital

To optimize the weighting coefficients, a customized objective function was defined as a weighted sum of penalty functions following:

$$\min obj = \sum_i K_i \cdot P_i \tag{3}$$

where the adopted penalties were:

1. P_1: approximated demand model error, i.e.: $error = \frac{1}{n}\sum_{ij}^{n}\left(\frac{\hat{V}_{ij}-V_{ij}}{\mathrm{V}_{ij}}\right)^2$
2. P_2: squared difference between approximated and reference total number of passengers
3. P_3: squared difference between approximated and reference cumulative passenger distribution
4. P_4: squared difference between approximated and reference cumulative passenger distribution on main routes
5. P_5: R^2 correlation coefficient.

It is difficult to obtain a perfect match of the reference travel demand data. One main reason is because the Swedish travel demand is very concentrated on few routes between main cities (see the plots on the far left in Figure 7 and Figure 8), whereas the remaining routes only account for a very limited volume. However, as shown in Figure 6, the final gravity model captures fairly well the main characteristics of the reference data, both in terms of total passenger volume and individual demands on main routes. The reference data has been filtered by a minimum number of passengers, as indicated on top of each one of the plots in Figure 6. The reason is that below a minimum number of passengers it is possible to assume that it would never be thinkable to establish an air link, so it was chosen to let the optimizer neglect those routes. Since the smallest aircraft that was considered has capacity for 9 passengers and assuming a target load factor around 90%, a minimum of 16 passengers can required on each route. This is the value that has been used to filter the data prior to optimizing the gravity model, but in Figure 6 different filtering limits are used to show how well the optimized model fits the data depending on which routes are considered. Also, the fourth penalty term in the objective function was tailored to focus on the three major routes, which can be seen in the third plot in Figure 6, where only the routes with at least 200 passengers are shown. It is clearly visible that the small difference in cumulative passenger distribution is mostly accountable to the smaller routes.

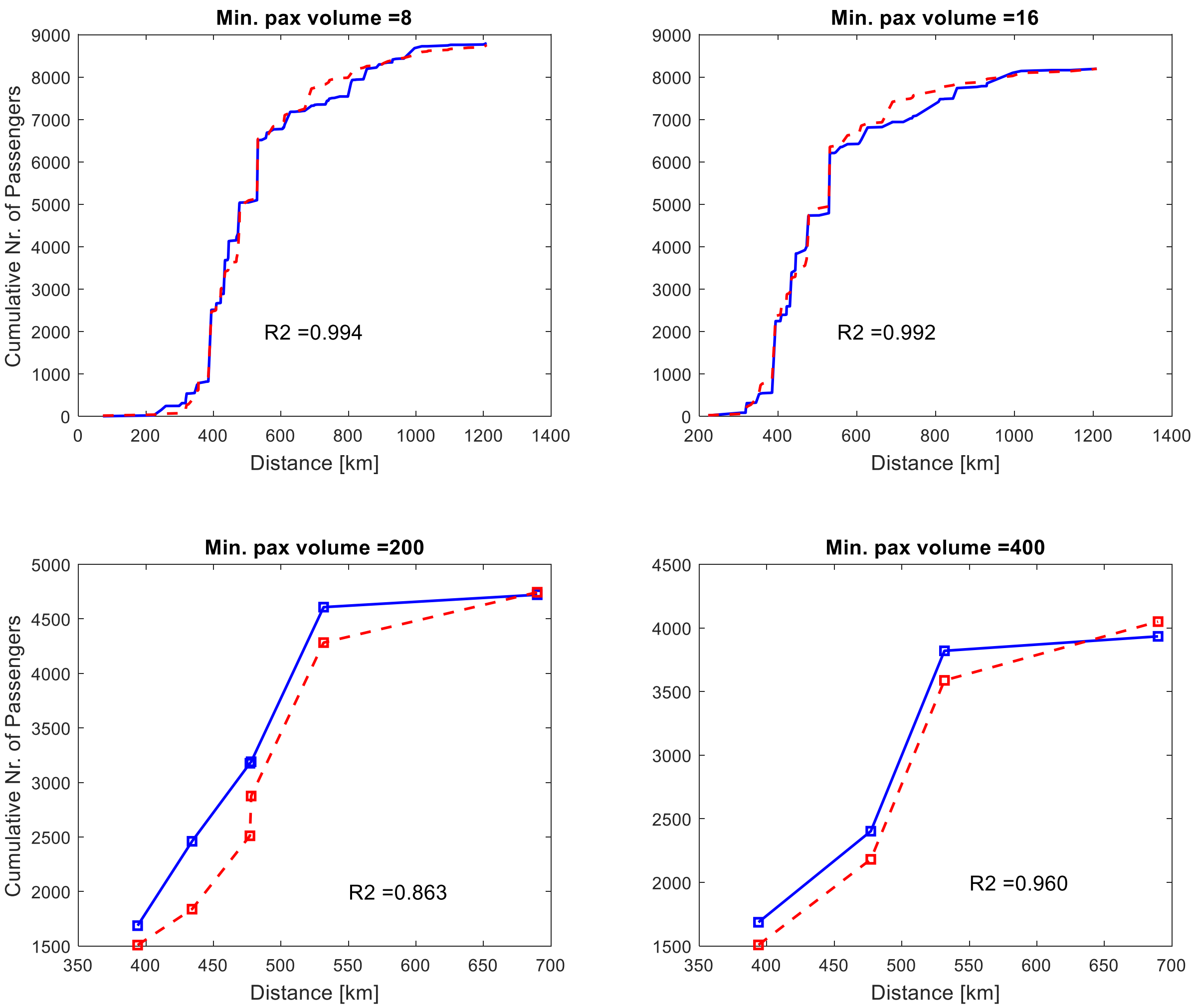


Figure 6 Comparison between approximated gravity model (blue solid line) and reference travel demand data (red dashed line), calculated in number of round-trip passengers a day on each route

The plots in Figure 7 and Figure 8 show instead the actual and estimated passenger volumes between the 41 considered Swedish airports (indexed from 1 to 41 in x and y axis). The colour scale in Figure 7 indicates the number of passengers a day for each pair of airports. It is evident that most of airport's pairs have a very limited volume, also confirmed in the frequency plots presented in Figure 8, where the bins show the frequency (in logarithmic scale) of the number of passengers. The map and plot to the far right in Figure 7 show for each airport pair the difference between reference and estimated data, again providing indication of fair agreement between the two models.

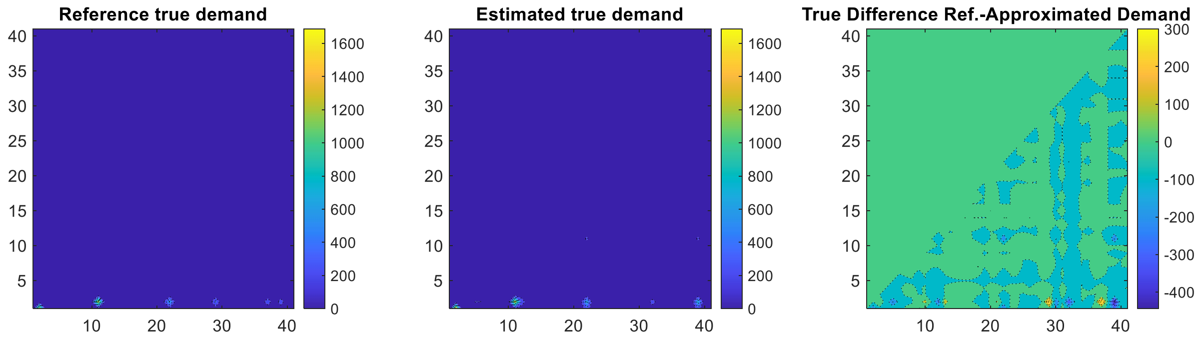


Figure 7 Comparison between reference and estimated passenger volumes

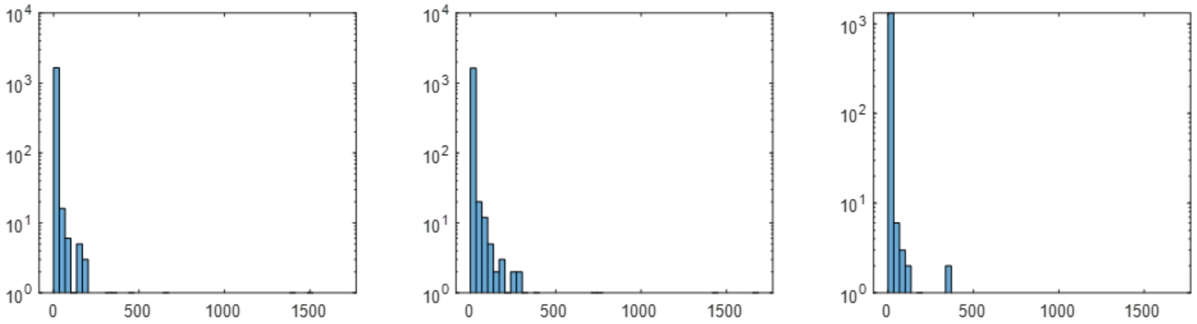


Figure 8 Passengers volume frequency over routes' length for reference and estimated models

C. Finnish Demand Model

To create a demand model for Finland it was hypothesized that Sweden and Finland are sufficiently similar with respect to travel patterns, infrastructural availability and topography. Therefore, it was assumed that travel demands in the two countries would be influenced in a similar way by similar factors. This is an assumption that has not been verified, and could of course have a major impact on the modelling and analysis results, but was imposed by the lack of other sources for travel demand predictions. Taking this for valid, the same gravity coefficients as optimized for the Swedish case were employed. Population and GDP data was collected for Finnish municipalities from Statistics Finland [33] and then forward-dated to year 2045 using growth predictions as for the Swedish case. Similarly, to Sweden, the number of hospitals and universities wasn't changed between today and 2045. The obtained demand model was finally "resized" so that the total domestic passenger volume would match historic data, adjusted by a 11% growth factor to correspond to total future demand's predictions.

It was not possible to carry out a validation of the model, for two main reasons. The first one is that current travel data show passenger volumes on active routes, whereas the model that was developed is intended to represent the travel demand between all available airports. This means that current data measures travel "as an outcome" while the model describes the "willingness" to travel. The second, indeed linked to the first one, is that the number of routes in the model is significantly larger than in current data, so comparison was only sparsely possible, but showed however encouraging trends similarities.

D. Norwegian Demand Model

As already mentioned, available travel for Norway shows that there are fundamental differences compared to Sweden and Finland. Therefore, a different approach was adopted.

Domestic air travel in Norway serves already today a much larger number of destinations. Hence, it was assumed that in year 2045 the number of routes would be the same, which equals to imagining that no major road and railroad infrastructural transformation will occur until then. Then, the passenger volumes on each domestic route were increased in accordance to travel growth predictions made by [34][38].

VI. Flight Operations Models

From the passenger demand models, an allocation of suitable aircraft types (as described in Table 1) is needed to meet the demand on the different routes. A baseline scenario was created assuming all aircraft fuelled by SAF. It can be noted that the maximum aircraft size is the equivalent of an Airbus A319 aircraft with a capacity of 150 passengers, which is a limitation resulting from the work presented by Jouannet [11], and based only on the Swedish transportation case. It has been observed that a larger aircraft would be suitable on some routes in Norway due to a higher volume of passenger on some routes. In all cases, for the present project, a minimum load factor of 0.65 was required, taking into consideration that such a low load factor would require governmental subsidies in order to be commercially viable. However, all routes below 150 km were disregarded from aircraft-allocation perspective, because on such short distances it was considered that other modes of transportation would be more realistic. Please note that this was not done for Norway, where even shorter flights can be feasible to travel across fjords that may represent significant hinders for ground transportation. The effects on passenger demands from this filtering can be seen in Table 3. Further details on the impacts on each country are available in the sections below.

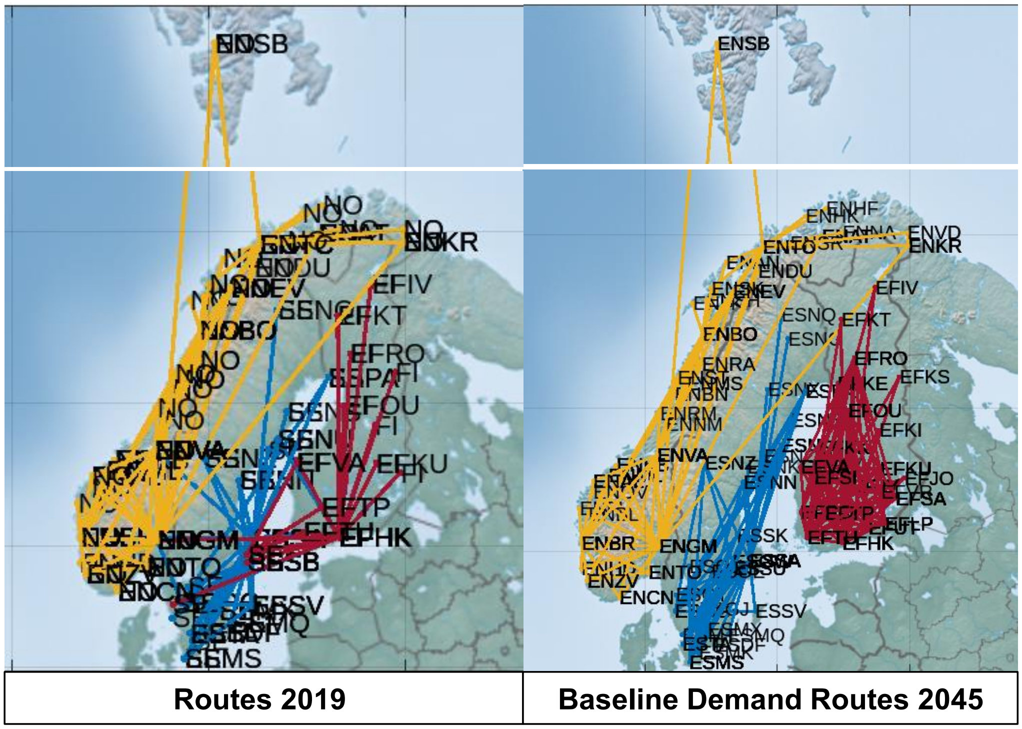
In the scope of the project, no considerations were done on creating an operational network with possible hubs, neither were any economic viability analyses. Within this study, results have been based merely on meeting a certain demand to create a first understanding of the possibilities offered by notional eco-friendly aircraft as described in Table 1. The logic for allocation of aircraft size to the different routes was as following:

1. Create a baseline with 100% SAF fuelled aircraft and minimize number of trips on each route and allocate the largest aircraft that ensures a load factor larger than 65%
2. Re-allocate battery-electrical aircraft instead of SAF fuelled ones on as many routes as possible, using range as limiting factor. Two sub-cases are considered:
    a. Maximum usage of electric aircraft, in which battery powered aircraft are allocated on any route that is within range
    b. "Realistic" usage of electric aircraft, in which a maximum total number of 15 flights per day is imposed (three two-hour slots a day with departures every 30 minutes)
3. On the routes still operated by SAF-fuelled aircraft, re-allocate hydrogen fuel cells aircraft whenever allowed by range limitations. The same two sub-cases as above were applied
4. On the routes still operated by SAF-fuelled aircraft, re-allocate liquid hydrogen combusting aircraft whenever allowed by range limitations. The same two sub-cases as above were applied.

Table 3 Passenger demand data for the three countries before and after imposing constraints on minimum number of passengers and minimum travel distance

	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

All the routes provided by the demand model described in previous chapters operated by SAF-fuelled aircraft as in the baseline scenario are shown in **Error! Reference source not found.** in comparison with historic data from 2019 according to Eurosat [9].



Routes 2019

Baseline Demand Routes 2045

Figure 9 Aircraft routes per country, based on historic data (left) and on the demand model (right)

A. Results for Sweden

As seen in in Table 3, raw data from the demand model gives 820 possible routes, whereas by applying a minimum number of passengers of 24.6 pax/day (i.e. 2 flights per day, with the smallest aircraft at the lowest load factor), and a minimum distance of 150 km, reduced this to 46 routes. Interestingly, this only reduced by 15% the total passenger demand, which is similar to results presented in reference [11]. The cumulative passenger per kilometre chart presented in Figure 10, shows that a few routes account for a significant amount of all travels. The top 10 routes out of 46 total represent 71% of all passengers in Sweden and the top three routes represent 46% of all passengers. The two major routes are Stockholm-Göteborg and Stockholm-Malmö, accounting for 38% of all aircraft passengers in Sweden. Since train infrastructure does exist on these routes, and being the travel time about 3 and 4 hours respectively, it is possible that air travel could be replaced at least partially if the planned high-speed train would be finalized. Many flights are between 450 and 600 km long, which correspond to where a large time saving can occur compared to terrestrial alternative modes. These routes link main larger city pairs and their metropolitan capture areas, and are a reflection of the skewed population repartition so typical of Sweden, see Figure 1. Most of the passenger demand on routes over 600 km represent a small portion of the demand volume, which is the reason why there a certain number of SAF-fuelled aircraft with low capacity remain at the end of the allocation process. In this study, economic viability considerations were not taken into consideration, although poor economy is the main issue affecting low-volume and long-distance routes, which has been a troubling aspect in many actual commercial regional flights in Sweden where almost no airline operates anymore small aircraft on certain routes, as shown in Figure 9.

The fallout from the aircraft allocation adopted in this study is shown in Figure 13 and the total number of flights allocated per type of aircraft is presented in Table 4. It can be seen that the battery-electrical aircraft represent barely any cumulative passenger volume in Sweden, reflecting that many routes have a range that is not that viable for this type of aircraft when only direct flights are considered. Hydrogen fuel cells powered aircraft represent the largest type in Sweden, which is a combination of size and range constraints in the demand model.

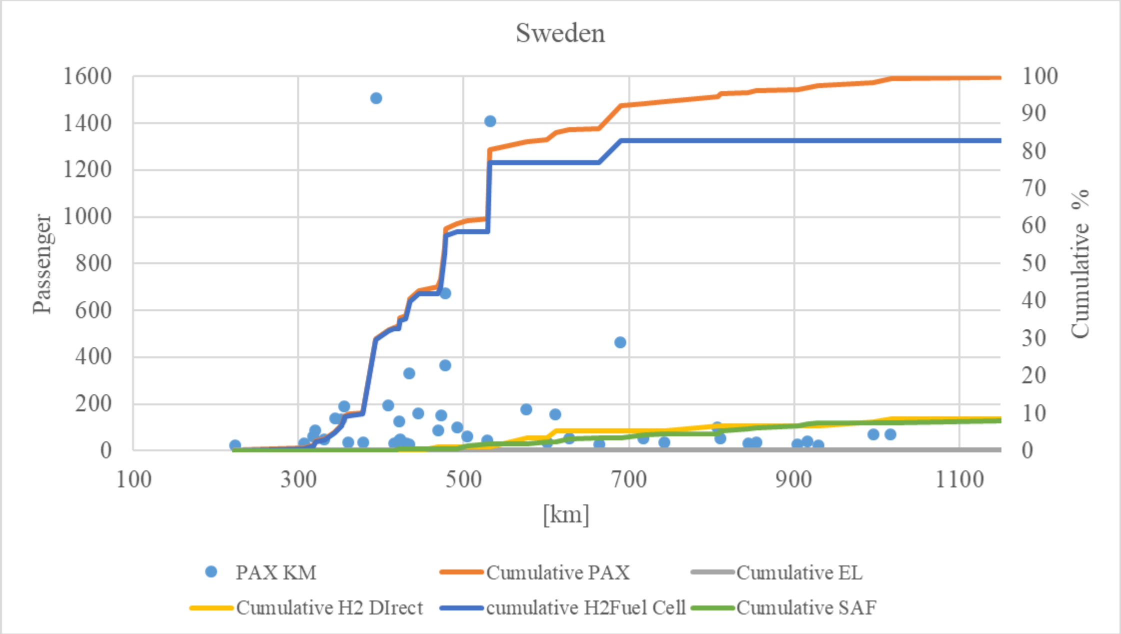


Figure 10 Passenger per kilometres and cumulative passenger, total and per type of technology for Sweden

The remaining SAF-fuelled aircraft on low-capacity routes are due to the nature of Sweden and the long range required to connected distant airports although with limited passenger demand, which are the typical characteristics of north-south connections, as seen in Table 4. By creating a network with strategically chosen hubs, it would be possible to obtain a different distribution, where the SAF fuelled aircraft could be replaced by other types. However, as stated previously, analysing and developing a hub-based transportation model was not in scope. In Table 4 it can clearly be seen that the Swedish demand is divided into two distinct categories, small volume requiring up to 34-seat aircraft, a middle market with some 76-seat requirements.

Table 4 Aircraft type and capacity and daily trip distribution for Sweden based on demand model

A/C Capacity	EL	H2	H2FC	SAF	Total
9	4			44	48
19			18	6	24
34			30	8	38
50		8			8
76			78		78
90		2			2
120		2			2
150		0			0
Total	4	12	126	58	200

SAF Only	
A/C Capacity	Total
9	48
19	18
34	14
50	10
76	2
90	10
120	16
150	32

B. Results for Finland

As seen in in Table 3, raw data from the demand model gives 361 possible routes, whereas by applying a minimum number of passengers of 24.6 pax/day (i.e. 2 flights per day, with the smallest aircraft at the lowest load factor), and a minimum distance of 150 km, the number of routes are reduced to 87, resulting in a reduction of 13.6% of passenger demand. The cumulative passenger per kilometre chart presented in Figure 11, shows that there are not few dominant routes as was the case in Sweden. However, the historic data from 2019 (see Figure 9) showed a much smaller number of routes only connecting the main airports with Helsinki airport being the hub, whereas in the developed demand model, the resulting network is distributed representing a point-to-point type of operations. The top 10 routes account for 27% of all passengers in Finland and the top three routes only 10% of total passengers. Compared to the neighbouring countries, the top three routes are less dominant, with the majority of passengers' volume concentrated on routes between cities with a distance under 400 km. Table 5 present the total number of flights allocated per type of aircraft in the Finnish future scenario. It is interesting to observe that in Finland there is a clear opportunity for battery-electric aircraft, since the distribute nature of the demand favours operations with small aircraft on shorter routes (see Figure 11).

Table 5 Aircraft type and capacity and daily trip distribution for Finland based on demand model

A/C Capacity	EL	H2	H2FC	SAF	Total
9	26		10	4	40
19	28		28	2	58
34	98		68	2	168
76			122		122
90		2			2
Total	152	2	228	8	390

SAF Only	
A/C Capacity	Total
9	14
19	18
34	14
50	30
76	8
90	24
120	50
150	44
Total	202

In Finland, as for the other Scandinavian countries studies herein, the very high representation of smaller aircraft is not surprising due to the low population density and relative long distances. However, this does not take into account the cost analysis that would be required to understand the commercial viability of those smaller routes. In a recent study by Justin et al. [15] it is shown that smaller aircraft could be profitable in the right geographical context and with the right cost/miles and passenger. It is possible that similar opportunities could be applicable in the Scandinavian countries as well.

It can be noted that cumulative passenger volume flown with the battery-electric aircraft represents slightly more than 20% of the total demand and is based on travels under 300 km. Typically, this would be a market that could be subject to competition from transportation by roads and train if ticket price and time saving were considered. Hydrogen fuel cells powered aircraft account for the majority of routes, with about 70% of all passengers.

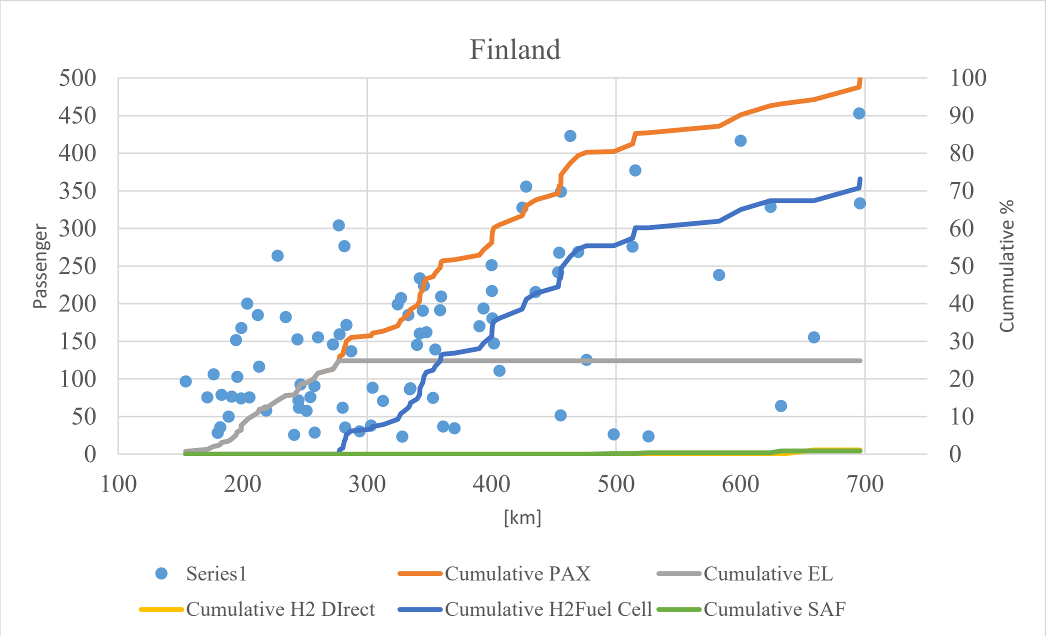


Figure 11 Passenger per kilometres and cumulative passenger, total and per type of technology for Finland

C. Results for Norway

The cumulative passenger per kilometre chart presented in Figure 12, shows that the majority of demand is concentrated on few routes around 400 km. The top 10 routes out of 101 total represent 72% of all passengers in Norway and the top three routes represent 39% of the total volume. What is peculiar to Norway and in contrast with Sweden and Finland, is that all routes could potentially be operated by airplanes driven by batteries or hydrogen. It seems technologically possible to replace all SAF fuelled aircraft by other more sustainable types. Despite the high number of battery-electrical aircraft, only about 10% of the total passenger volume is covered by these smaller aircraft. Again, this is a consequence of the dominance of the three main routes with very high passengers' volumes, where small aircraft are note suitable. The high-capacity demand on certain routes and due to the constraints imposed by the aircraft described in Table 1, are the reasons why a very high number of direct combustion hydrogen aircraft are adopted in Norway. There is also a clear indication that an even larger aircraft types than what was considered in this study would be needed on the very passenger demanding routes (as can be seen by the high number of flights necessary to meet the demand on these routes).

Table 6 Aircraft type and capacity and daily trip distribution in Norway for a maximum electrical aircraft case

A/C Capacity	EL	H2	H2FC	Total
9	10			10
19	36			36
34	268		30	298
50		4		4
76			616	616
90		8		8
120		308		308
Total	314	320	646	1280

SAF Only	
A/C Capacity	Total
34	4
50	26
76	8
90	32
120	50
150	594
Total	714

Based on the fact that the aircraft allocation in this approach favoured electrical aircraft with a high allowable trip per routes, as reflected in Table 6. It could easily be argued that another repartition would be preferable. One main remark is the fact that a sustainable number of routes would be better served by and aircraft with a capacity larger than 150 passengers, based on the aircraft distribution if only SAF would be considered.

From in Figure 12 it can be observed that a large part of the Norwegian domestic air travel demands seem to favour an aircraft with a relatively small range, also reflected in the large number of smaller aircraft with limited capacity. Domestic flights in Norway today are either operated by two types of airlines. Wideroe [36] is an airline operating mainly Dash-8 aircraft, with a majority of smaller variants with 29 seats. Wideroe has routes connecting all the smaller airports scattered along the coastline of Norway, flying short to medium ranges and relatively small passenger demands. Two other major airlines, Norwegian and SAS operate instead on the large volume routes and have a mixed fleet with significantly larger aircraft than Wideroe (such as Boeing B737-800 aircraft).

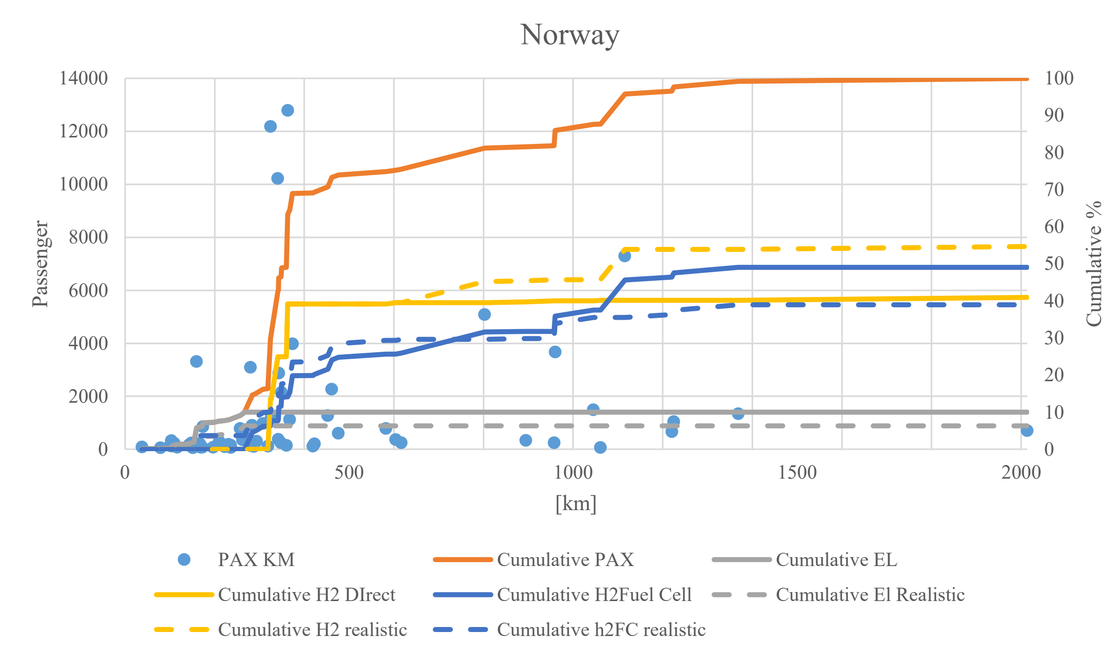


Figure 12 Passenger per kilometres and cumulative passenger, total and per type of technology for Norway

For the Norwegian case, two different aircraft allocation strategies were applied (called “EL” and “EL Realistic” in Figure 12). The allocation logics were presented above. When applying the same login as in Sweden and Finland, it was observed that no 150-passenger direct combusting hydrogen aircraft was selected even on the longer and higher passenger volume routes. To try alleviating this, a variant of the allocation logic was applied, called “Realistic”. The main difference was that in the “realistic” case, the algorithm was constrained not to choose too many smaller aircraft on relatively high-demand routes, and instead favouring the larger aircraft types, even if those aircraft could have flown the ranges required.

Finally, it can be also noted that due to the higher passenger volumes that characterize the Norwegian demand model, even a large number of battery-electric aircraft can’t account for any large portion of the total passenger demand.

Table 7 Aircraft type and capacity and daily trip distribution in Norway for a Realistic distribution

A/C Capacity	EL	H2	H2FC	Total
9	10			10
19	36			36
34	170		30	200
50		4		4
76			496	496
90		8		8
120		8		8
150		330		330
Total	216	350	526	1092

SAF Only	
A/C Capacity	Total
34	4
50	26
76	8
90	32
120	50
150	594
Total	714

VII. Discussion and Future Work

Demand model for three Scandinavian countries has been presented, limited to their domestic demands, with no consideration of the cross-border flights that could be possible. The future demand models represent a 2045 scenario and are derived from different sources. The Swedish model was developed by the Swedish Transport Administration and served as a base to develop gravity model coefficients that were then applied to Finland. Since Norway is characterized by very different travel patterns compared to Sweden and Finland, historic transport data was instead forward-dated to represent the Norwegian future demand.

Four types of propulsion systems have been applied on 8 different notional aircraft with varying sizes. These aircraft have been allocated to the future routes to meet the passenger demands trying to minimize emissions and offering as sustainable operations as possible.

Considerations on economic operational viability, electric power generation, hydrogen production and infrastructure impact and demand have not been included in this study.

With reference to Figure 13, results show that:

1. Sweden offers very limited opportunities for battery-electric aircraft due to the limited range performance which is necessary. Any battery evolution with higher specific energy density could change this result. Conversely, hydrogen fuel cell powered aircraft could meet most of the demand even on the longest routes
2. The Finnish demand model does not prioritize few main routes as in Sweden, but is more distributed, which favours the adoption of aircraft with smaller capacity. However, hydrogen fuel cell powered aircraft seem to have a strong case, as they account for the majority of the passenger demand
3. Norway has already today a significantly more developed domestic air transportation network whereas the ground infrastructures and transportations are less viable. Due to its nature, the Norwegian market offers opportunities for both smaller electric aircraft and larger hydrogen powered ones. However, even if present in significant numbers, the battery-electric aircraft don’t account for a larger portion of the total passenger volume.

Results presented in this paper are strongly dependant on the demand models employed, on the aircraft allocation logic that was developed and on the performance assumed for the different aircraft. The lack of verified future demand models for the Scandinavian countries required to make important assumptions that could have a significant effect on the obtained results. Another consequence was that the study was carried out on Sweden, Norway and Finland domestic air transportation demands separately, whereas a joined analysis of the whole region could have led to different conclusions.

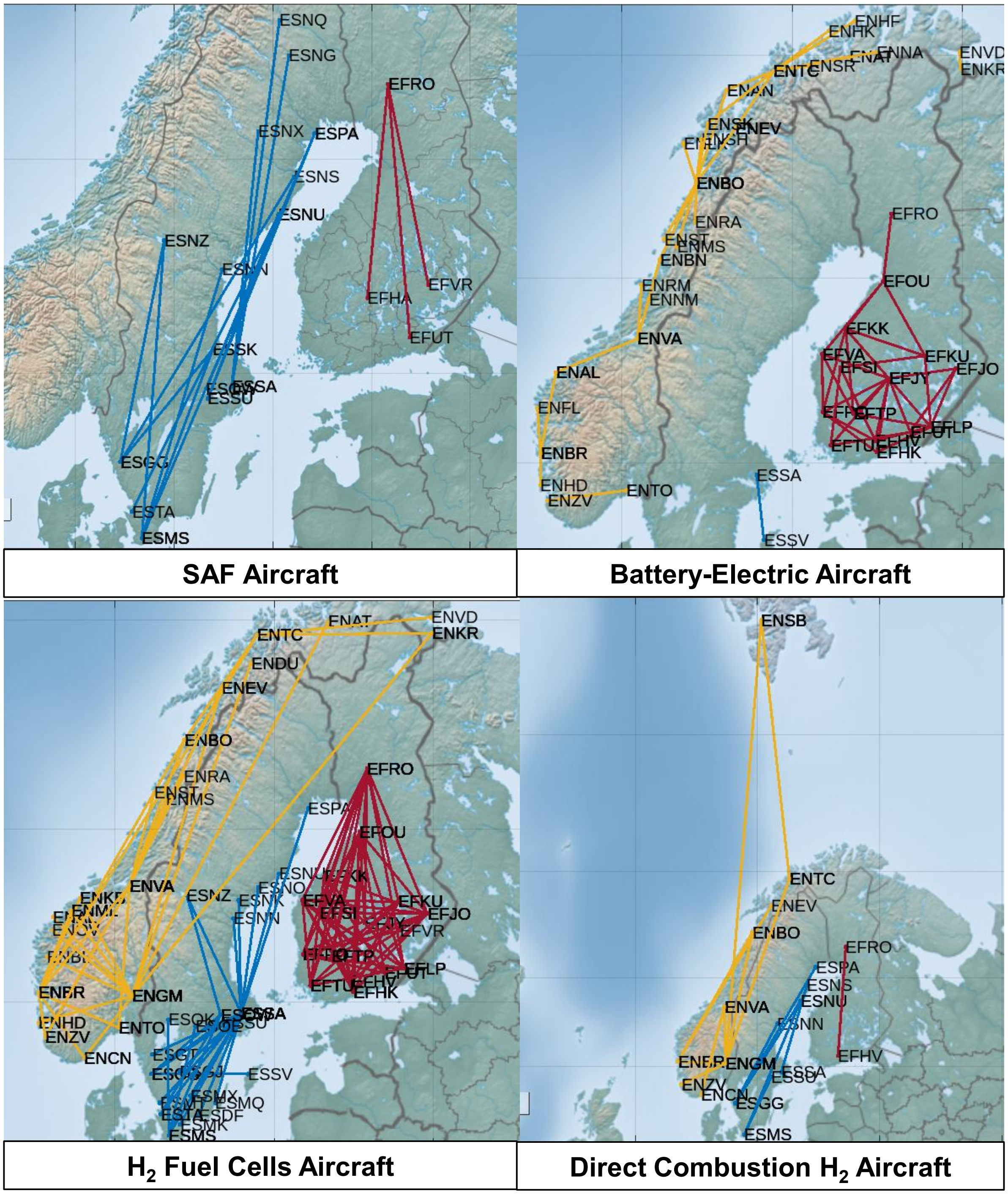
From the aircraft models perspective, it should be mentioned that the battery technology performance had a large impact on the results. This is common to studies of this kind, but it is worth repeating, since available battery energy density is one of the major limiting factors, and if unforeseen developments would be available in the future, results would be largely impacted.

Although not addressed in this study, infrastructural aspects such as production and distribution of hydrogen and electric power are certainly of utmost importance, both to assess the viability of sustainable aviation opportunities and to determine the true environmental impact of operations.

Also, in this study a low load factor was deemed acceptable, making the assumption that in the future domestic air operations will still be subsidized by governments to ensure critical connections in the region. Changing the minimum viable load factor would naturally also have a strong impact on the allocation of aircraft throughout the routes.

Finally, results in this study are only accounting for point-to-point operations. The study and development of networks could be of interest for future work, as well as other allocation logics.

From the literature it can be noticed that some cross border regions have address the possibilities that short flight could offered, as in the Kverken region that is described in the FAIR project. However this does not indicate whether the demand on these routes could have economic viability.



SAF Aircraft

Battery-Electric Aircraft

H_2 Fuel Cells Aircraft

Direct Combustion H_2 Aircraft

Figure 13 Resulting distribution of the four different aircraft propulsion technologies in Sweden. Norway and Finland

VIII. Acknowledgement

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