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ZERO-EMISSION REGIONAL AVIATION IN SWEDEN

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Abstract

Regional air operations, which can be defined as the transportation of passengers using smaller aircraft over short distances, have been overlooked in recent years by airlines focusing on high volume and profitable routes between large airports. Despite this shift of focus, the airport infrastructure still exists in many smaller communities between which demand for air travel exists. The emergence of new air vehicles designed for shorter routes could stimulate efficient and profitable operations, especially if they leverage currently underutilized and paid-for airports. However, new regional air operations need to be sustainable to be successful in a world striving for a carbon-neutral future, especially since air travel over short distances can be substituted by other means of transportation with a smaller environmental footprint such as cars, trains, or buses. Many different paths are envisioned to reach zero-emission goals. These range from technology advancements to new powertrain configurations, and from new transportation policies to new emission offsetting schemes. It is however not clear how these different paths interact and how solutions could be optimally combined. Analyses are therefore required to estimate future demand for air travel and to assess the feasibility of zero-emission regional aviation with the objective to support decision-making about viable and sustainable paths for new regional air operations. The developed modeling environment is implemented in Sweden and allows for an environmental assessment of various scenarios. Significant untapped demand is uncovered between smaller markets, and given fuel and energy consumption for these operations, it is likely that sustainable advanced regional air mobility will be possible in Sweden provided technology transitions can be made.

Keywords: Sustainability, Regional Aviation, Electrification, Hydrogen

1. Introduction

1.1 The role of aviation in global warming

While aviation emissions are only responsible for about 3% of global emissions, the global air travel and transport industry produced an estimated 32.6 billion tons of carbon dioxide emissions from 1940 to 2018 [1]. In the EU, the transport sector represented almost one third of total carbon emissions in 2018, mainly because of its dependence on oil [2]. The aviation sector contributed to around 13% of those transport emissions, or 4% of the EU's total emissions. This contribution may be small but as other sectors decarbonize and air transportation continues to grow, it is likely to reach significant levels in the future. The path toward decarbonization in the aviation sector appears to be more complicated and uncertain than for other transportation modes like road traffic, where technology solutions such as the electric car already exist. To further put the emissions of aviation into perspective, carbon dioxide makes up only one third of aviation emissions [1]. The remaining two thirds of environmental pollution come from contrails, nitrous oxide, water vapor, and other hydrocarbons. These gases have an impact on global warming by increasing radiative forcing, the change in the amount of energy radiated toward the ground. Given the radiative forcing associated with aviation emissions, it becomes evident that this sector is and will continue to be a major contributor to global warming.

1.2 Impact on regional aviation

Having stated the actual impact of aviation emissions, a move toward more environmentally-friendly, zero-emission aviation appears to be necessary and urgent if the world wants to reach its goal of remaining below 2°C of warming in 2100 according to the Paris agreement. It is very much in the interest of the aviation sector to work towards that goal. Regulations aimed at developing net-zero emissions aviation already exist:

- Norway announced that all of its short-haul flights would have to be electric by 2040 [3]
- France has banned domestic air travels that could be made by train within two-and-a-half hours [4]
- The "flygskam" or "flight-shaming" is spreading across Europe and some travelers are thinking twice before flying given the environmental footprint of air travel
- The International Air Transport Association (IATA) declared in October 2021 that the aviation sector will aim to reach carbon neutrality by 2050

These new regulations and views disproportionately affect regional aviation (assumed to include aircraft with a capacity up to 150 passengers in this study), as it could be more easily replaced by other means of transportation such as the train, car, or bus, which may be cheaper and more environmentally friendly than air transportation. Consequently, if regional aviation does not try to tackle emissions, it is at risk of disappearing due to policies and societal concerns.

1.3 New advanced air mobility operations

Beyond changing regulations and consumer views, operations are also expected to evolve in the coming decades. Millions of dollars are invested in the design of new advanced regional air mobility vehicles with the intent of reenergizing operations from more convenient airports. Non-stop flight operations between these small regional airports could provide travel time savings for air passengers who prefer not to connect at large airport hubs to get to their destination. They are ubiquitous all over the world, and in particular in Europe where 50% of the population lives within 30-minute of a regional airport [5]. This observation, combined with the possibility of substantially lower operating cost for new regional aircraft, creates potential for new economically viable operations at these underutilized airports. *Underutilized airports* can be defined as small regional airports that feature limited or no domestic services, despite having the capability to support these flights. Additional demand for regional operations from these airports could exacerbate the previously stated environmental concerns with aviation. For these new regional operations to be accepted, sustainability aspects need to be accounted for early on and must be considered.

1.4 Project goal

Many different paths are envisioned to reach goals for zero-emission aviation. For example, IATA historically defines four main pillars in their strategy for carbon emissions reduction including technology, aircraft operations, infrastructure, and economic instruments [6]. Considering the multi-dimensional path forward towards environmentally-friendly aviation, decision-makers could benefit from a holistic analysis of the future of the regional aviation industry as it progresses toward the goal of zero-emission. This holistic analysis should capture new policies and strategies, new breakthroughs in technologies, the competition from other modes of transportation, and the growth of aviation demand. Thus, the goal of the project is to provide decision-makers a framework to assess the effects of their environmental policies or strategies, technology investments, and new operations on the regional aviation market. The technology and aircraft operations pillars are the two pillars that are most aligned with the goal of this project as well as what may be realistically achievable in the coming timeframe. New technologies are already being pursued in Europe which could impact current operations. The scope of this study includes the life cycle emissions of every energy source consumed in aircraft operations. Land usage, water usage, and investment requirements to produce alternative energy sources as well as infrastructure requirements to operate new technologies at every airport were not considered. Additionally, economic analysis was not explored. These aspects would need to be added for a full-scale feasibility assessment of zero-emission regional operations.

This study will aim to answer how much emissions reduction is feasible given technology implementation while accounting for expected changes in aircraft operations.

The completed work will develop the capability for demand and emissions assessment, which future work can build upon to perform rapid zero-emission feasibility analysis. The use case will be Sweden for several reasons. First, the country and surrounding region is adapted to this project due to its aggressive goals for a sustainable future within the next few decades, and its current transportation systems which are already trying to address the problem of climate change. Additionally, the emergence of policies and technologies that could dramatically influence the aviation sector is already taking place in Sweden between the Swedish government's climate policy framework targeting net-zero greenhouse gas emissions by 2045, and the investment in the design of advanced regional air mobility vehicles by Swedish aerospace manufacturers such as Heart Aerospace. Second, there are many small regional airports already in Sweden that could be used to assess growing operations. Sweden is also centrally located in Scandinavia, surrounded by other areas of interest including Norway and Finland, which could be explored given the completed work is expanded upon. These areas could provide unique possibilities for solutions due to the impact of physical barriers such as mountains and separating bodies of water on regional transportation. The following sections will present literature review on key components to be considered, requirements for the analysis, and the methodology and subsequent details of the technical approach taken to solve the problem. Next, various scenarios will be defined and examined as they pertain to the use case to determine carbon emissions reduction and demand served.

2. Problem Formulation

2.1 Proposed regulations and technologies

Literature review regarding aviation policies reveals proposals with a wide range in severity for airlines. For example, less severe regulations include an environmental tax on plane tickets compared to more severe requirements to transition entire fleets of aircraft to cleaner propulsion by a given year. As mentioned previously, Norway is planning to have all short haul flights on electric aircraft by 2040. If these transitions are not made, some countries such as France have even proposed to completely ban flights up to certain distance. Many of these regulations are inherently connected to the emergence of various propulsion technologies in aviation including:

- Sustainable Aviation Fuel (SAF)
- Electrification
- Hydrogen

SAF is compatible with existing jet engine technology and fuel distribution architecture. It produces similar emissions to jet fuel when burned during combustion, but life cycle emissions are considered to be reduced compared to jet fuel because materials used to produce SAF are grown and harvested. Electrification corresponds to the use of electric powertrains to power propeller-driven aircraft, significantly reducing emissions when electric supply is less carbon-intensive than jet fuel. Finally, hydrogen can either power a fuel cell that generates electricity or be used as fuel for combustion with oxygen in a modified gas turbine. No carbon is emitted in the burning of hydrogen, however hydrogen production is very energy-intensive. All of these technologies are not expected to produce zero emissions over the course of their life cycle, but they are expected to aid in reducing total carbon emissions from aviation. Some offsetting schemes would be required to reach true net-zero. Because each technology has its own advantages, disadvantages, and realistic applications, they will be assessed under a variety of scenarios to determine impact on carbon emissions reduction.

2.2 Modeling requirements

The study aims to model and forecast regional travel demand in Sweden while estimating the corresponding carbon emissions per mode of transportation, with a focus on air transportation. The analysis will be compiled into a dynamic dashboard to enable what-if, sensitivity analysis. The end-user of this dashboard will be able to select different technologies such as alternative propulsion devices to modify the emissions associated with air travel, as well as policies to influence travel demand. Several requirements were identified in order to first estimate demand for different modes of transportation and then to calculate emissions associated with passenger travel. The first requirement involves estimating the number of passengers per day for each route. The estimation must take into account the effect of new regional air operations between currently underutilized airports. The second requirement is to estimate the emissions per day of each mode of transportation for each route, given an estimated number of passengers per day. Due to the focus on technology infusion for air emissions reduction, there is a need to differentiate the passenger seat category or aircraft gauge that the passengers are flying in. This need arises because not every category of aircraft will likely use every technology. For example, larger regional aircraft will likely not be electrified in the coming timeframe. Moreover, even for aircraft using the same technology, the computation of fuel and energy consumption will vary for different seat categories. To address this need, regional aircraft categories are identified as the following:

- Small regional aircraft: 9-pax and 19-pax
- Regional propeller aircraft: 50-pax and 80-pax
- Medium range aircraft: 150-pax

2.3 Methodology

Successive modeling steps were identified in the process required to meet the stated requirements:

1. **Travel demand modeling** will be estimating the demand for travel in Sweden using a conventional four-step 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. **Operations modeling** will assign a frequency of flights and an aircraft gauge for each market depending on the demand found in the previous step. This is performed according to desired operating conditions including a minimum and maximum flight frequency per day and passenger load factor.
3. **Emissions modeling** will compute the carbon emissions associated with each mode of transportation. Emissions associated with alternative propulsive devices such as hydrogen and electric powertrains will need to be considered.
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 Bokeh Python library was chosen to build this dashboard.

The modeling steps are linked together before visualization as depicted in Figure 1. More details on the steps in the proposed methodology will constitute the next sections of this report, followed by the use of this methodology to analyze the use case.

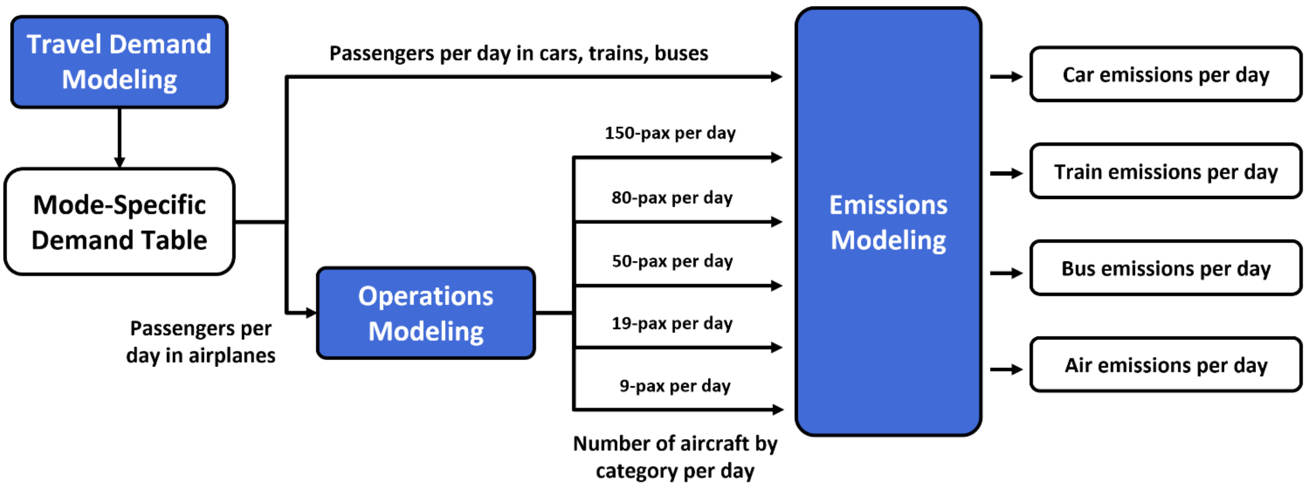

Figure 1: Modeling steps

3. Travel Demand Modeling

3.1 Demand assessment

Traditionally, travel demand is assessed using the four-step model of trip generation, trip distribution, mode choice, and route assignment [7]. This traditional model can answer the question of reducing greenhouse gas emissions in a region by a given percent when paired with an emissions model [8]. Trafikverket, the Swedish Transport Administration, has shared a dataset including predicted daily passenger flows for all modes of transport between origin-destination pairs at the municipality level for domestic travel in Sweden. The passenger flows have already been divided between various modes of transport including car, train, bus, and airplane. This dataset thus serves as a complete assessment of trip generation, trip distribution, and mode choice. However, some assumptions were used to generate these passenger flows that are inconsistent with expected future concept of operations for advanced regional air mobility. Namely, only markets with current regularly scheduled flights were accounted for. The use of smaller electric aircraft and other new vehicles that allow for environmentally-friendly travel across short distances could however stimulate air demand along new markets. The presence of such technologies and the presumably added convenience of traveling between small, underserved airports may significantly impact the mode choice of passengers. As a result, mode choice must be revisited to forecast changes in the division of passenger flow created by new technologies and operations. This approach assumes that these new conditions do not alter total passenger flow and that trip generation and trip distribution performed in the provided dataset do not need to be reexamined. Estimated travel demand for each mode from the Swedish Transport Administration dataset is recombined and a new mode split is performed.

3.2 Mode choice modeling

The prediction of which mode of transportation is selected by a passenger is commonly made through a logit model. First, utility of each transportation mode must be determined. This utility can be broken down into the many attributes of the passengers and transportation mode including: income, value of travel time savings, number of persons in traveling party, number of nights away, travel time, travel cost, travel comfort, frequency of service, and number of transfers. A generalized cost of travel, consisting of just two major components, can be used to simplify the utility function [9]. These two major components include actual trip cost (fuel, ticket price, etc.) and time cost associated with the trip (dependent on individual's value of time). This generalized cost is represented in Equation 1, where GC_m is the generalized cost of travel of mode m, C_m is the trip cost, VT is individual value of time, and T_m is the trip time.

$$GC_m = C_m + VT \cdot T_m \tag{1}$$

Equation 1 assumes completely rational decision making with regards to cost when it comes to passenger mode choice, however convenience or familiarity can often play a role. Thus, a probabilistic-based choice model will be used in place of a deterministic-choice model to account for uncertainty. Actual utility U_m of mode m is thus calculated using Equation 2, where α and β_m are calibration parameters.

$$U_m = \alpha \cdot GC_m + \beta_m \tag{2}$$

Calibration is performed using a small sample of routes from the original Swedish Transport Administration dataset where air transportation is already available in addition to other modes. The α and β_m parameters that maximize the likelihood the sample was generated from the model are determined with a maximum likelihood technique [9]. The probability that a passenger chooses air travel, P_{air}, can then be modeled using Equation 3.

$$P_{air} = \frac{1}{1+e^{U_{car}-U_{air}}+e^{U_{train}-U_{air}}+e^{U_{bus}-U_{air}}} \tag{3}$$

3.3 Trip time modeling

For travel by car, travel time equals the time spent driving between origin and destination. For rail or bus travel, travel time equals the sum of any time spent traveling to a nearby station, time spent riding the train or bus, and any time spent transferring. For air travel, travel time is the sum of the driving time from the origin to the nearest airport, time spent at the airport, time spent flying, and the driving time from the nearest airport to the destination. Driving time and route distance along origin-destination pairs are extracted from OpenStreetMap.[1] Expected travel times by train and by bus are acquired from the Rome2Rio multimodal transport engine.[2] Rome2Rio estimates are generally conservative, including time for transfers. In order to estimate the time associated with traveling via train or bus for every origin-destination pair, a sample of routes is used to generate expected transit time for train and bus as a function of distance travelled. The sample covers various distances along many different origin-destination pairs in Sweden. Lastly, total time for air travel is calculated by summing block flight time with driving time to and from the airport. In order to estimate block flight time, frequently scheduled regional flights in Scandinavia are first identified using the FlightAware flight tracker.[3] Next, the direct distance and times for each flight are recorded. The expected block flight time along an origin-destination pair can then be modeled as a function of direct distance.

3.4 Trip cost modeling

The expected costs associated with each travel mode are also acquired from Rome2Rio using the same sample used to estimate travel time. Rome2Rio provides estimated trip cost as a range that one would expect to pay when travelling. For travel by car, estimated fuel cost for a standard sedan vehicle is calculated from collected annual data on global fuel prices simplified into a per kilometer model. Train and bus travel cost is estimated using collected historic pricing samples of routes for each operator simplified into a per kilometer model. Similarly, cost to fly is also estimated using historic pricing samples simplified into a per kilometer model, based on the cost of one-way travel in economy class and booked in advance. From the ranges displayed by Rome2Rio, median price estimates are gathered for the routes sampled and modeled as a function of distance travelled.

4. Operations Modeling

The goal of the operations modeling step is to associate the air demand found in travel modeling to how many aircraft are flying. This is then fed into the next step, emissions modeling, in order to compute the emissions due to air travel. It is crucial when assigning flights to the air demand to distinguish between different categories of aircraft. The end-user of the dashboard will be able to infuse diverse propulsion technology onto the aircraft, depending on their size. A narrow-body aircraft, e.g., A320neo will have different technology expectations than a smaller short-haul aircraft such as the Metroliner. For example, it is expected that narrow-body aircraft will be not electrified but rather use hydrogen propulsion. These two propulsive technologies will not have the same emissions computation. For this reason, it is important to rigorously allocate the different categories of aircraft to the air demand. The seat categories considered for this project are 9, 19, 50, 80 and 150-pax aircraft. It is assumed that only one type of aircraft can fly each route.

4.1 Route filtering

Before allocating the seat categories to air routes, minimum desirable operations are first specified. For each seat category c, an average passenger load factor l_c and a minimum flight frequency per day $f_{min,c}$ are assumed. The minimum demand $d_{min,c}$ on a route to fly the seat category is then found with Equation 4.

$$d_{min,c} = c \cdot l_c \cdot f_{min,c} \tag{4}$$

For example, minimum viable operations of a 19-pax aircraft at 90% load factor ($l_{19} = 0.9$) and 2 flights per day ($f_{min,19} = 2$) could be specified. The minimum demand for the 19-pax aircraft to be

[1] www.openstreetmap.org
[2] www.rome2rio.com
[3] www.flightaware.com

viable is therefore $19 \cdot 0.9 \cdot 2 \approx 35$ passengers per day. Next, the minimum viable demand for a route is found as the minimum of all $d_{min,c}$ for $c \in \{9, 19, 50, 80, 150\}$. This minimum is then used to filter out routes that are deemed not profitable for air operations. The air passengers on these filtered routes are rerouted on other modes of transportation using relative probabilities calculated during the travel modeling step. The goal of filtering is to ensure that at least one seat category will be able to meet desired frequency for viable operations, otherwise flights will not be generated and ground transport is used as a substitute.

4.2 Assignment of aircraft gauge

For each remaining route r with an air demand d_r, the seat categories are filtered depending on the runway length constraints of the airports. The minimum required runway length for operation of an aircraft seat category is determined by the takeoff ground roll and distance to clear a 50-ft obstacle. Weather conditions can impact these requirements, but they were not considered in this analysis. The required runway lengths used are shown in Table 1. In Sweden, only the 150-pax aircraft is largely problematic for some small regional airports.

Table 1: Assumed runway length requirements for various aircraft seat categories

Aircraft Seat Category	*Minimum required runway length (m)*
9-pax	630
19-pax	870
50-pax	1100
80-pax	1280
150-pax	1950

Next, the remaining seat category that should fly r is found by computing the eventual flight frequency for each seat category needed to serve d_r passengers. That is to say, for each category c, the potential flight frequency on r, $f_{r,c}^*$, is given by Equation 5.

$$f_{r,c}^* = \frac{d_r}{c \cdot l_c} \quad (5)$$

This potential frequency is then compared to $f_{min,c}$ and a suggested maximum frequency $f_{max,c}$ specified in the assumptions. The seat categories that fall within $f_{min,c} \leq f_{r,c}^* \leq f_{max,c}$ are retained. The final category which will fly the route r depends on which assignment strategy or allocation logic is preferred. The default strategy is to favor the use of the largest aircraft possible considering the minimum frequency requirement, which mostly corresponds to maximizing range and demand that can be served. An alternative strategy is to fly the category of aircraft that would emit the lowest carbon emissions on the route, among the remaining categories. The potential emissions of a category are computed by averaging the emissions of that category on that route of each propulsive technology, weighted by the technology mix of the scenario. For example, for a scenario where the 9-pax category is 30% battery-powered and 70% SAF, the average emissions of the 9-pax category on route r is found using Equation 6. This low emission strategy is explored in the case study section as an alternative to the default.

$$emissions_{r,9\,pax} = 0.3\ emissions_{r,9\,pax,battery} + 0.7\ emissions_{r,9\,pax,SAF} \quad (6)$$

5. Emissions Modeling

After having modeled future traffic demand, the next step is to estimate emissions associated with transportation. The travel demand and operations modeling result in passenger travel made via car, train, bus, and aircraft between any pairs of origin-destinations that are considered. Thus, it represents the input for emissions modeling, which consists of computing the emissions for each mode of transportation as a function of distance.

5.1 Air transport emissions

For air transportation, once the number of passengers traveling on each route is known, the method in operations modeling described previously predicts which aircraft capacity is needed on each route and at what frequency it should be operated. To determine life cycle emissions per unit of energy consumed during operations, energy consumption must be calculated as a function of mission range, aircraft category, and powertrain technology. Hybrid propulsion technologies are not being considered in this study due to modeling complexity. Additionally, energy required by avionics, lighting, environmental control, etc. was not considered. Five propulsion types, characterized by energy carrier have been selected including:

- **Jet-A fuel:** Current standard fuel for aviation that can be used in all aircraft segments.
- **SAF:** A drop-in fuel that has almost the same chemical composition and properties as conventional jet fuel. As such it can also be used for all aircraft.
- **Electric batteries:** Considering current and projected evolution of battery technology, a fully battery powered aircraft in the 9 to 19-pax segment is deemed feasible in the next 20 years. Bigger electric aircraft are not considered.
- **Hydrogen fuel cell:** Promising technology for small to medium size regional aircraft (9 to 80-pax). Probably not viable in the next 20 years for larger jet aircraft.
- **Hydrogen turbine:** Could replace traditional gas turbine, especially on large jets where batteries or fuel cells would not be a viable solution.

For each aircraft technology, a dedicated method to compute energy consumption on a given mission is established, with details provided in the following sections. Once the energy consumption is determined, the associated emissions can be computed by using Table 2.

Table 2: Life cycle emissions by energy carrier in Sweden [10]

Energy carrier	***Life cycle emissions (gCO₂ /MJ)***
Jet-A Fuel	89
SAF	20
Electricity	10
Liquid Hydrogen [4]	13

5.1.1 Conventional and SAF powered aircraft

The methodology chosen to model the consumption of aircraft using traditional jet fuel is based on the Breguet range equation and associated aircraft mass equation represented below by Equations 7 and 8.

$$R = \frac{V}{g}\frac{1}{SFC}\frac{L}{D}\ln\left(\frac{1}{1-\frac{m_{fuel}}{m_{TO}}}\right) = \frac{\Delta h_{fuel}}{g}\eta\frac{L}{D}\ln\left(\frac{1}{1-\frac{m_{fuel}}{m_{TO}}}\right) \tag{7}$$

$$m_{TO} = \frac{m_{payload} + m_{empty}}{1-\frac{m_{fuel}}{m_{TO}}} \tag{8}$$

Given a range R, lift-to-drag ratio $\frac{L}{D}$, and specific fuel consumption SFC or overall efficiency η, Equation 7 allows for the estimation of the fuel mass ratio. The chosen approach to estimate consumption requires that different reference aircraft be defined, one for each aircraft gauge, using the required performance characteristics. Those reference aircraft are based on aircraft that are currently flying, and any characteristics that were used to model fuel consumption and battery sizing can be seen in Table 3. Battery and hydrogen consumption will be explained in more detail in the following sections.

[4] Value for hydrogen is obtained by assuming an 80% efficient electrolysis production followed by a 90% efficient liquefaction, both using Swedish grid electricity

Table 3: Technical characteristics of notional reference aircraft [11]

	Beechcraft B200	*Metroliner*	*Fokker 50*	*ATR 72*	*A320neo*
Seat category	9	19	50	80	150
Lift-Drag ratio	12	11.5	13	17	18.8
Payload mass (kg)	1000	2214	5000	7550	15311
Cruise altitude (m)	7600	7600	7600	8300	11800
Cruise velocity (m/s)	145	143	147	141	230
Propulsive efficiency	0.85	0.85	0.85	0.85	0.58
Fuel cell efficiency	0.6	0.6	0.6	0.6	0.6
SAF/Jet-A SFC (g/kNs)	1.00E-05	1.50E-05	1.30E-05		1.57E-05
SAF/Jet-A turbine thermal efficiency				0.35	
Electric motor efficiency	0.9	0.9	0.9	0.9	0.9
Empty mass fraction	0.6	0.6			
Battery energy density (Wh/kg) [5]	400	400			
Maximum m_{TO} increase due to battery (%) [6]	100	100			
Desired design range for battery (km)	500	500			
Required reserve holding time (min)	30	30	30	30	30
Alternate airport distance (km)	50	50	50	50	200

Solving Equations 7 and 8 yields the mass of fuel consumed for Jet-A fuel powered aircraft. Having almost the same chemical composition and properties as conventional jet fuel, the consumption rate of SAF is very similar to a Jet-A engine with a difference in energy consumption on the order of 0.1% [12]. This methodology thus allows for the estimation of the consumption of hypothetical SAF powered aircraft. It is important to note however that the Breguet range equation assumes that the aircraft is in cruise condition during the whole flight. Takeoff, climb, descent, and acceleration phases as well as taxiing are not taken into account by this equation. To account for this, a few additional steps were added to the methodology. Once a first estimate of the total weight has been established, the potential and kinetic energies gained during climb and acceleration is computed. It is then possible to compute the mass of fuel required to provide this energy with the engine efficiency and the fuel energy density. This mass is then added to the total weight, and the whole process is repeated to track additional mass that has to be brought to altitude and accelerated. The loop stops when the increment in fuel required falls below a threshold. This allows for a rough estimate of the extra fuel consumption associated with climb and acceleration, even if it does not measure the change in lift-to-drag ratio or SFC during those phases. An additional fuel mass corresponding to 5% of the block fuel is also added for taxiing. Another factor that needs to be accounted for, especially for short range missions on small aircraft, is the mass of the reserve fuel. In order to address this, the designed algorithm begins by running a first mission corresponding to the reserve mission. This mission is defined by a distance to an alternate airport and a holding time. The speed used during hold is the maximum endurance speed, which is assumed to be equal to $1.3V_{stall}$. The distance to an alternate airport plus the holding speed multiplied by the holding time yields a required reserve range. The mass of the fuel for the reserve mission can then be computed by solving Equations 7 and 8, which finally can be added to the empty mass, as it will not be consumed. The main mission is then run with this updated empty mass.

After implementation, this algorithm for computing conventional jet fuel was tested against a FLOPS model for a notional 150-pax aircraft.[7] FLOPS is a sizing and analysis program developed by NASA, which can compute the fuel consumption of an aircraft for a given mission. The fidelity of FLOPS can be considered as higher than the modified Breguet range method presented. Depending on the mission range the difference between the models is contained in a +/- 8% margin. The fuel consumption of the modified Breguet range method is underestimated in very short missions and overestimated for very long missions relative to FLOPS. This is most likely due to the simplistic approach for taking the climb segment into account. This margin is considered reasonable and small

[5] Estimated
[6] Estimated
[7] NASA Flight Optimization System (FLOPS) Software v.9

enough for the purpose of the study in comparing high-level decisions on technologies and fuel sources for various aircraft categories. No FLOPS models were available for comparison in smaller aircraft categories, but an effort was made to adjust their aircraft characteristics to best match available fuel flow data from Eurocontrol for climb and cruise segments [13].

5.1.2 Hydrogen gas turbine powered aircraft

A Cryoplane study conducted by Airbus in 2002 tried to assess the feasibility of hydrogen powered aviation [14]. Several aircraft running on hydrogen turbine were modeled and analyzed. One of the main takeaways of the Cryoplane study was an estimation of the variation in energy consumption when using a hydrogen turbine compared to conventional fuel. Results of this effort are summarized in Table 4. This estimation was in fact made for multiple aircraft gauges, from business jet and small regional aircraft to twin aisle long haul jets. Knowing this variation, the baseline energy consumption with jet fuel, and the energy content of hydrogen, it is possible to determine the amount of fuel required for hydrogen powered aircraft.

5.1.3 Hydrogen fuel cell powered aircraft

Other important results of the Cryoplane study include the variation in empty mass of the aircraft due to the presence of heavy and voluminous hydrogen tanks. While the variation in energy consumption estimated by the study is only valid in the case of hydrogen turbine, the discovered empty mass variation can be used to compute the empty mass of hydrogen fuel cell aircraft by applying the variation to reference aircraft empty weight. Once the new empty weight is known, the Breguet range equation can again be used to determine the hydrogen required on any given trip. Additionally, a different overall efficiency is used accounting for the fuel cell and electric powertrain. The same methodology as for conventional aircraft can then be applied.

Table 4: Assumed impact of hydrogen powertrain on energy consumption and empty mass [14]

Aircraft Segment	*Δenergy / pax.km*	*Δempty mass*
9 to 19-pax turboprop	14%	16.5%
50 to 80-pax turboprop	18%	23.0%
150-pax turbofan	10%	25.1%

5.1.4 Battery powered aircraft

Electric aircraft energy consumption can also be modeled with a revised version of the Breguet range equation and corresponding mass equation which accounts for the mass of the aircraft remaining constant during the whole flight [15].

$$R = \frac{u_{battery}\,\kappa}{g}\eta\frac{L}{D}\frac{m_{battery}}{m_{TO}} \quad (9)$$

$$m_{TO} = \frac{m_{payload}}{1-\left(\frac{m_{empty}}{m_{TO}}+\frac{m_{battery}}{m_{TO}}\right)} \quad (10)$$

The percentage of the battery to be used for flight excluding the safety reserve, κ, can be determined for a given range using Equation 9, in which $u_{battery}$ is the battery energy density. Knowing the battery capacity and the amount of electricity consumed during the flight, the associated emissions can be calculated by extension. This process requires that the battery mass ratio and the battery capacity are identified. Thus, the battery is first sized for a desired design mission range for the electric aircraft by solving for the battery mass ratio in Equation 9. Once the battery mass ratio is known, Equation 10 can be used to find the takeoff mass by making an assumption of the empty mass ratio. A conservative assumption is made that the empty mass ratio remains constant relative to current aircraft. If the desired design range for which the battery is sized is too large, it could lead to impractical or infeasible aircraft with no room for passengers. Thus, a maximum increase in takeoff mass with respect to current reference aircraft is specified. This is equivalent to fixing a minimum payload fraction. If the mass of the sized aircraft surpasses this limit, then the design range is reduced by 5 km steps and the sizing process is reperformed until the mass falls below the limit.

5.2 Road and rail emissions

An effort is also made to estimate the emissions of regional traffic of cars, trains, and buses over the routes considered to put air transport emissions in perspective and determine how operations and technologies actually impact the transport system as a whole. The traffic modeling step provides daily passenger flow via car, train, and bus over various routes. The emissions from each trip are computed by multiplying the trip distance by an average emission coefficient in gCO_2/pax-km, which will be different for the various modes. The default coefficients are based on the current average emissions of cars, trains, and buses and expected technological improvements or changes over the next 20 years can be specified for any analysis performed. For travel by car, a different coefficient for electric and conventional cars that consume gasoline is considered, with the ability to specify the percentage of electric cars in the market. Decision-makers will be able to take into account the technological improvement in the final dashboard by modifying these average emission coefficients to see the effects of different scenarios.

Table 5: Ground transport emissions in Sweden [16] [17] [18]

Ground transport mode	***Life cycle emissions (gCO_2 /pax-km)***
Gas car	182
Electric car	47
Train	0.0039
Bus	16

6. Case Study

First, the impact of making convenient regional airports in Sweden available to passengers for non-stop travel is highlighted by comparing results using the original Swedish Transport Administration forecast versus those generated using the developed mode choice model. The results of this developed model will then serve as an advanced regional air mobility baseline scenario for the 2045 timeframe. Next, sensitivity analysis for various paths to zero-emission regional aviation will be performed to assess and quantify the impact of introducing SAF, battery technology, and hydrogen. After all technologies have been introduced, changes in fleet assignment strategy and battery energy density will be explored for further reduced emissions and increased ability to serve air demand, respectively. Metrics of interest include air demand served, air emissions, total transport emissions, as well as number of flights by seat category. Fuel/energy required for flight operations will also be discussed relative to current or near-term supply. Modeling assumptions for these comparisons will be held constant and can be found in Tables 6 and 7.

Table 6: Demand and operations assumptions

Demand		**Operations**	
Value of time (USD/hour)	25	Passenger load factor (%)	70
Time spent at stations (min)	20	Minimum frequency (flights/day)	2
Time spent at airports (min)	75	Maximum frequency (flights/day)	8

Table 7: Vehicle and technology assumptions

Vehicle & Powertrain		**Technology Improvements**	
Electric car market share (%)	90	Change in ICE car emissions (%)	-15
Battery pack specific energy density (Wh/kg)	400	Change in aircraft SFC (%)	-10

Value of time is determined using expected average hourly wages in the 2045 timeframe assuming historical trends continue [19]. Average passenger load factor is also taken from previously reported aviation trends in Sweden [20]. Time spent at stations and airports is estimated and minimum and maximum frequency per day were selected to best represent reasonable advanced air mobility operations. Specifically, a minimum frequency of 2 flights per day was chosen to ensure practical operations are assessed for regional air mobility. For example, not all passengers may be able to fly at the same time of day, and any commuters would need to be able to return to their point of origin. Electric car market share is also estimated and battery pack specific energy density is assumed based on current assessment of battery energy requirements for all-electric operations [21]. Change in car emissions was determined by assuming a continuation of an approximate 3% reduction in the last 5 years [22]. Finally, change in cruise SFC is based on medium progress for turboprop aircraft in ICAO's long-term aspirational goals for 2045 [23].

6.1 Impact of advanced regional air mobility

Non-stop air travel is permitted between a total of 44 airports in Sweden within the developed mode choice model to account for growth in emissions due to advanced regional air mobility services. These airports are displayed on a map of Sweden in Figure 2, which depicts those which currently maintain active domestic service.

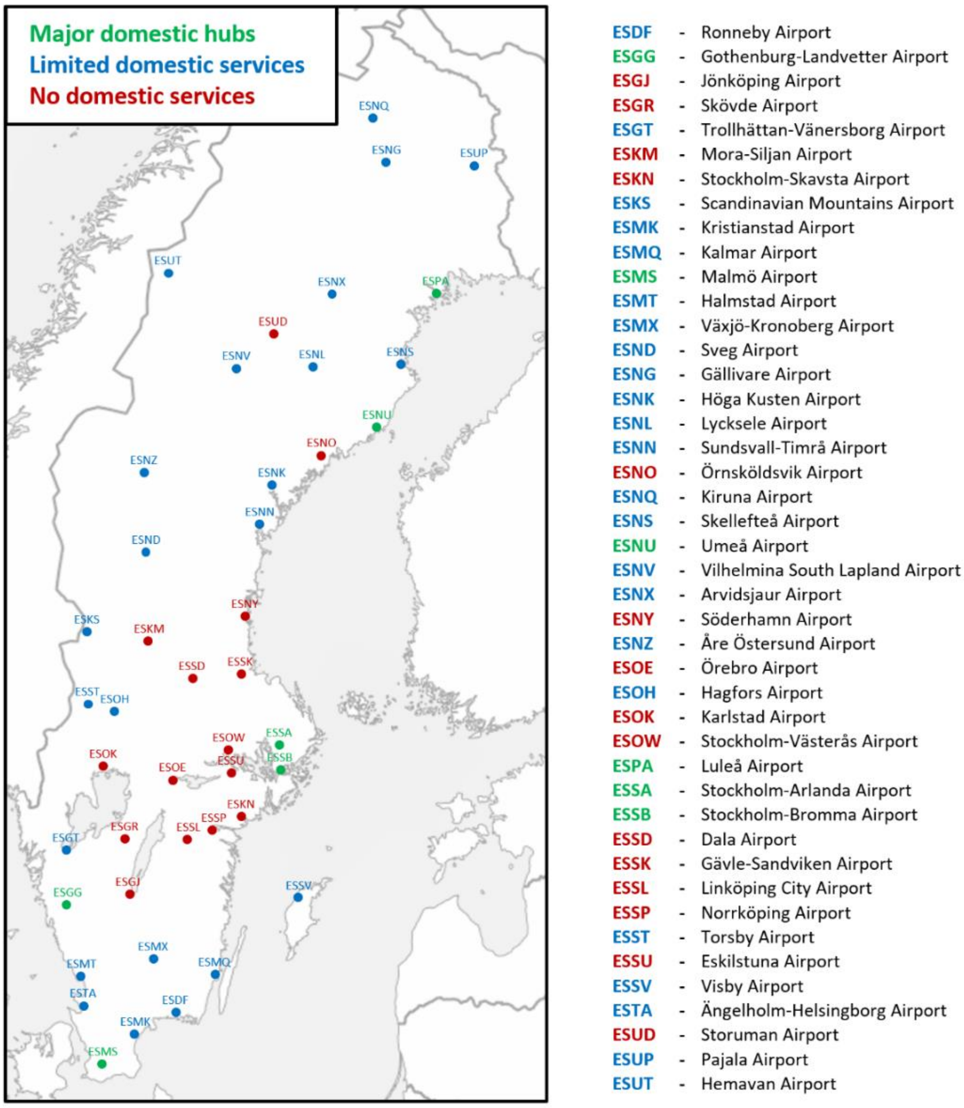

Figure 2: ICAO registered airports in Sweden included in the analysis [24]

Results of allowing passengers to fly non-stop between the nearest airport to their origin and the nearest airport to their destination in the mode choice model (Advanced Regional Air Mobility Baseline) are shown relative to results generated using the original estimate of demand (Swedish Transport Administration Forecast) in Table 8. Under the 70% passenger load factor assumption and requirement for a minimum frequency of 2 flights per day for any given market, only 183 of the possible 1,892 markets in Sweden have sufficient demand using the Swedish Transport Administration forecast. This number increases to 437 markets when passengers are given the ability to fly directly out of more convenient regional airports.

Table 8: Comparison between original dataset and developed mode choice model

	Swedish Transport Administration Forecast	Advanced Regional Air Mobility Baseline
Air demand (pax/day)	9141	16358
Air emissions (tCO_2/day)	618	968
Total emissions (tCO_2/day)	2162	2211
Number of 9-pax (flights/day)	148	586
Number of 19-pax (flights/day)	149	439
Number of 50-pax (flights/day)	33	48
Number of 80-pax (flights/day)	43	58
Number of 150-pax (flights/day)	25	18

The use of underutilized airports to stimulate air travel leads to a rise in air demand of 79%. This corresponds to a rise in air emissions of 57% and a rise in total emissions of 2.3%. A sharp increase in the number of 9-pax and 19-pax flights is found compared to moderate increases in 50 and 80-pax flights. A drop in 150-pax flights is recorded likely due to decreased traffic congestion at major hubs. The convenience and expected travel time savings for passengers to fly has a very significant impact on travel demand in Sweden. A sample of routes between previously underutilized airports showing now sufficient air demand for service according to the operations assumptions made is displayed in Figure 3.

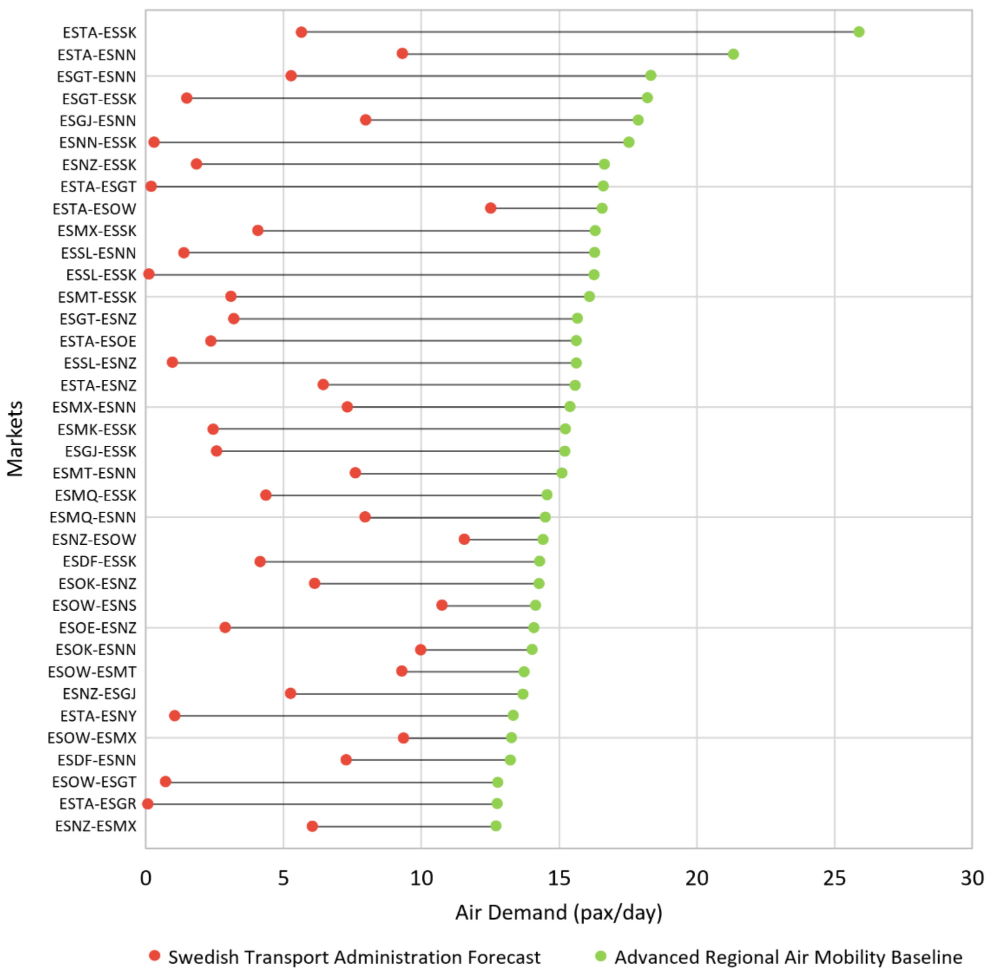

Figure 3: Change in air demand for a sample of routes between small regional airports

6.2 Impact of SAF, battery, and hydrogen technologies

The Swedish government has already started promoting the use of biofuels and SAF, and is aiming for fossil-free domestic aviation by 2030 [25]. Thus, it is likely that SAF will be used for domestic flights completely in place of Jet-A fuel by 2045 if production is sufficient. With regards to battery powered regional aircraft, there are many projects in development across the world such as Eviation's Alice[8], Bye Aerospace's eFlyer[9], and Heart Aerospace's ES-19[10]. These projects are expected to fly their first prototype in the next 5 years with an entry into market around 2030. New battery powered aircraft can be expected to enter the market at a rate corresponding to the renewal of the active fleet. Approximately 65% of the 9 and 19-pax fleet is identified as being able to be renewed as electric aircraft by 2045, given a retirement cycle of 25 years and that all new aircraft introduced in these categories are electric aircraft after 2030. This is derived from the assumption that a maximum of 20% of the fleet can be renewed every 5 years after the entry date, and that 5% of some existing aircraft can be retrofitted. As stated previously, hydrogen can be burned in a traditional gas turbine or it can be used in a fuel cell to produce electricity that will drive electric motors. The maturity levels of these two pathways are however not identical. Fuel cells are already widely used in ground transport applications despite their low specific power for use on an aircraft. Thus, it is commonly assumed that this technology will be integrated on small aircraft first. On the other hand, the specific power of a hydrogen gas turbine is not a limitation even for big aircraft, but the maturity level is lower. For these reasons, this study considers the use of hydrogen gas turbine only on 150-pax aircraft and the use of hydrogen fuel cell only on smaller aircraft categories. For developing a hydrogen turbine 150-pax aircraft and a 50 to 80-pax hydrogen fuel cell aircraft, the most notable project is Airbus ZEROe[11]. This program aims for an entry into market of a fuel cell regional turboprop by 2035, and a hydrogen turbine powered aircraft by 2040. By again assuming a retirement cycle of 25 years, a 45% fuel cell integration in the regional turboprop (assuming a 5% retrofit) and a 20% integration of hydrogen turbine in the fleet is identified as plausible by 2045. Additionally, the remaining 35% of the 9 and 19-pax fleet can be moved to hydrogen fuel cell. Finally, the rest of the fleet in Sweden would then use SAF to meet Sweden's requirements for fossil-free aviation. Four scenarios representing various levels of technology implementation are shown in Tables 9, 10, 11, and 12 to assess sensitivity in the results.

Table 9: Jet-A Fuel scenario

Seat Category	*Jet-A Fuel [%]*	*SAF [%]*	*Battery [%]*	*H_2 Fuel Cell [%]*	*H_2 Turbine [%]*
9-pax	100	0	0	0	0
19-pax	100	0	0	0	0
50-pax	100	0	0	0	0
80-pax	100	0	0	0	0
150-pax	100	0	0	0	0

Table 10: SAF scenario

Seat Category	*Jet-A Fuel [%]*	*SAF [%]*	*Battery [%]*	*H_2 Fuel Cell [%]*	*H_2 Turbine [%]*
9-pax	0	100	0	0	0
19-pax	0	100	0	0	0
50-pax	0	100	0	0	0
80-pax	0	100	0	0	0
150-pax	0	100	0	0	0

[8] https://www.eviation.co/aircraft/
[9] https://byeaerospace.com/electric-airplane/
[10] https://heartaerospace.com/
[11] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

Table 11: SAF + Battery scenario

Seat Category	Jet-A Fuel [%]	SAF [%]	Battery [%]	H_2 Fuel Cell [%]	H_2 Turbine [%]
9-pax	0	35	65	0	0
19-pax	0	35	65	0	0
50-pax	0	100	0	0	0
80-pax	0	100	0	0	0
150-pax	0	100	0	0	0

Table 12: SAF + Battery + Hydrogen scenario

Seat Category	Jet-A Fuel [%]	SAF [%]	Battery [%]	H_2 Fuel Cell [%]	H_2 Turbine [%]
9-pax	0	0	65	35	0
19-pax	0	0	65	35	0
50-pax	0	55	0	45	0
80-pax	0	55	0	45	0
150-pax	0	80	0	0	20

Due to the range limitations of battery powered aircraft, a decrease in the number of flights occurs for the 9 and 19-pax categories for the SAF + Battery and SAF + Battery + Hydrogen scenario as seen in Figure 4. Number of flights for other categories is unchanged and remains constant across all scenarios. The impact on key metrics is shown in Figure 5. The electrified 9-pax aircraft has a maximum range of 427 km and the 19-pax aircraft has a maximum range of 340 km at the 400 Wh/kg pack level battery energy density specified. However, when accounting for reserve, the serviceable range is only 260 km and 150 km for the 9 and 19-pax aircraft, respectively. These ranges are likely lower than what is actually achievable with emerging electric aircraft but are largely the result of the conservative assumption that the empty mass fraction will remain similar to current as-built aircraft. This empty mass would need to be reduced to allow for larger batteries for increased range. Alternatively, battery energy density would need to improve beyond projected 400 Wh/kg at the pack level.

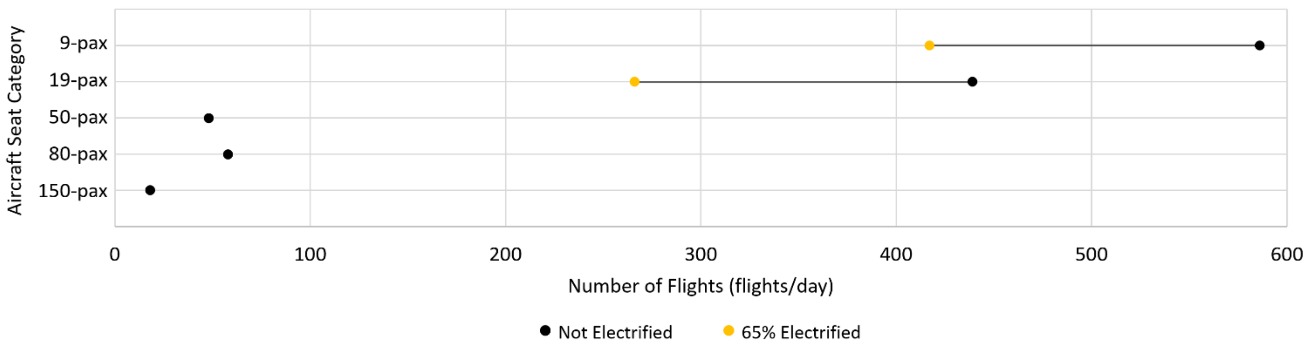

Figure 4: Impact on flights of electrifying 9 and 19 passenger aircraft

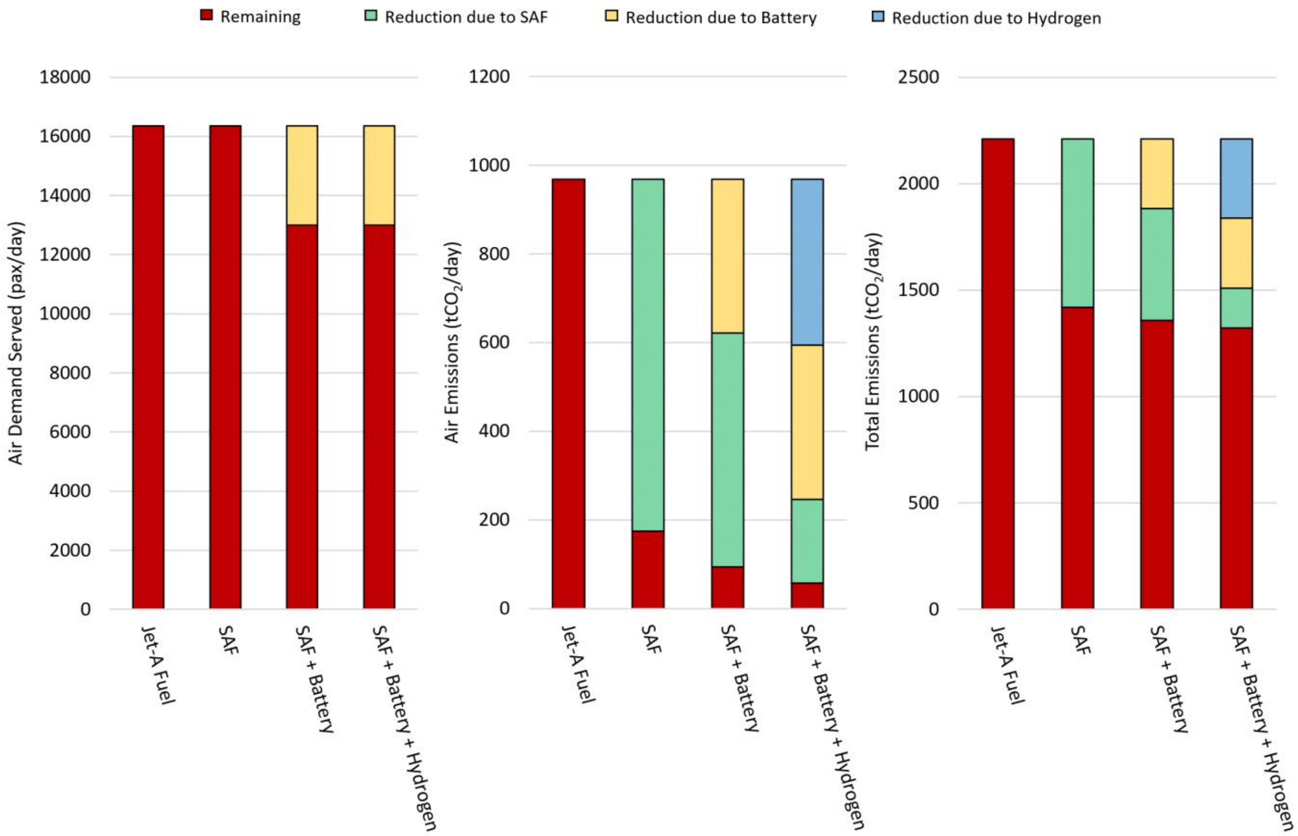

Figure 5: Impact on metrics of transitioning to SAF, Battery, and Hydrogen

An 82% reduction in air emissions and associated 36% reduction in total emissions is achieved by transitioning all aircraft from conventional fuel to SAF. According to the analysis, 189 metric tons of SAF per day would be required for the modeled operations. This resembles just under 70,000 tons of SAF for domestic operations annually. According to recent reports, Swedish Biofuels plans to bring 400,000 metric tons of SAF annually to the Swedish market within the next few years [27]. It is not clear though how practical or consistent this supply will be given SAF production conditions. Additionally, aviation will be forced to compete for biofuel with other modes or applications and SAF production can have other environmental impacts – land and water requirements for example – that could limit its availability. Thus, other technologies are being pursued. Electrification of aircraft is the next technology likely to be implemented at large scale. As shown in Figure 5, scenarios featuring battery powered 9 and 19-pax aircraft result in an expected loss of demand that can be served by approximately 20%. The shift towards majority batteries in place of SAF on the smallest categories results in an additional 46% reduction in air emissions (partly due to loss of flights) and 4% reduction in total emissions when compared to the all-SAF scenario. Total electricity required to fly all battery powered aircraft equals 0.13 GWh/day or 47.5 GWh annually, a mere fraction of Sweden 2020 wind and hydro power supply, which is recorded as 27,526 and 71,933 GWh, respectively [26]. Lastly, as hydrogen fuel cell and turbine are integrated, a further 38% reduction in air emissions and 3% reduction in total emissions is achieved relative to the SAF + Battery scenario. A total of 14 metric tons of hydrogen is consumed a day for these operations or 5,110 metric tons annually. To put this into perspective, 2021 Sweden hydrogen production is slated at 180,000 metric tons [28]. Because of Sweden's developing ability to produce and sustain renewable energy and fuel, it is likely near zero-emission regional aviation can be achieved, provided technology transitions can be made. It is important to note that offsetting schemes will still be required to achieve true net-zero.

6.3 Impact of aircraft gauge assignment strategy

Current air transport operations typically allocate aircraft to routes to maximize the overall economic benefit of airlines. The largest aircraft which can serve the most demand over an extended range is primarily chosen for use, not considering the difference in emissions per passenger between aircraft.

This could however be considered as part of the strategy to reduce the emissions of regional aviation, especially when new propulsion technologies are present. For example, as smaller aircraft are easier to electrify it could be beneficial to favor the use of smaller aircraft, even if it means a higher frequency of flights. Air traffic control regulations would need to be met for a complete assessment of the feasibility of this new strategy, but the technique can be applied to the SAF + Battery + Hydrogen scenario to determine impact while maintaining assumed bounds of 2 to 8 for frequency of flights per day. The change in number of flights by seat category of prioritizing the most emission efficient aircraft available is shown in Figure 6.

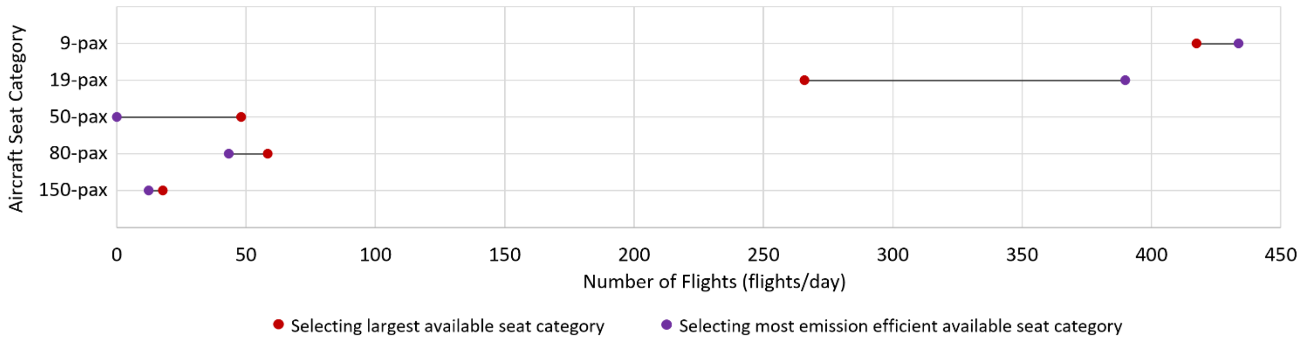

Figure 6: Impact on flights of prioritizing lowest emission vs. largest available seat category (SAF + Battery + Hydrogen)

The resulting impact on metrics is displayed in Figure 7. Prioritizing emission efficient aircraft, largely the 9 and 19-pax electric aircraft, leads to a reduction in 10% of air demand that can be served. A reduction in air emissions of 28% (partly due to loss of flights) and a 0.5% in total emissions is achieved due to this strategy.

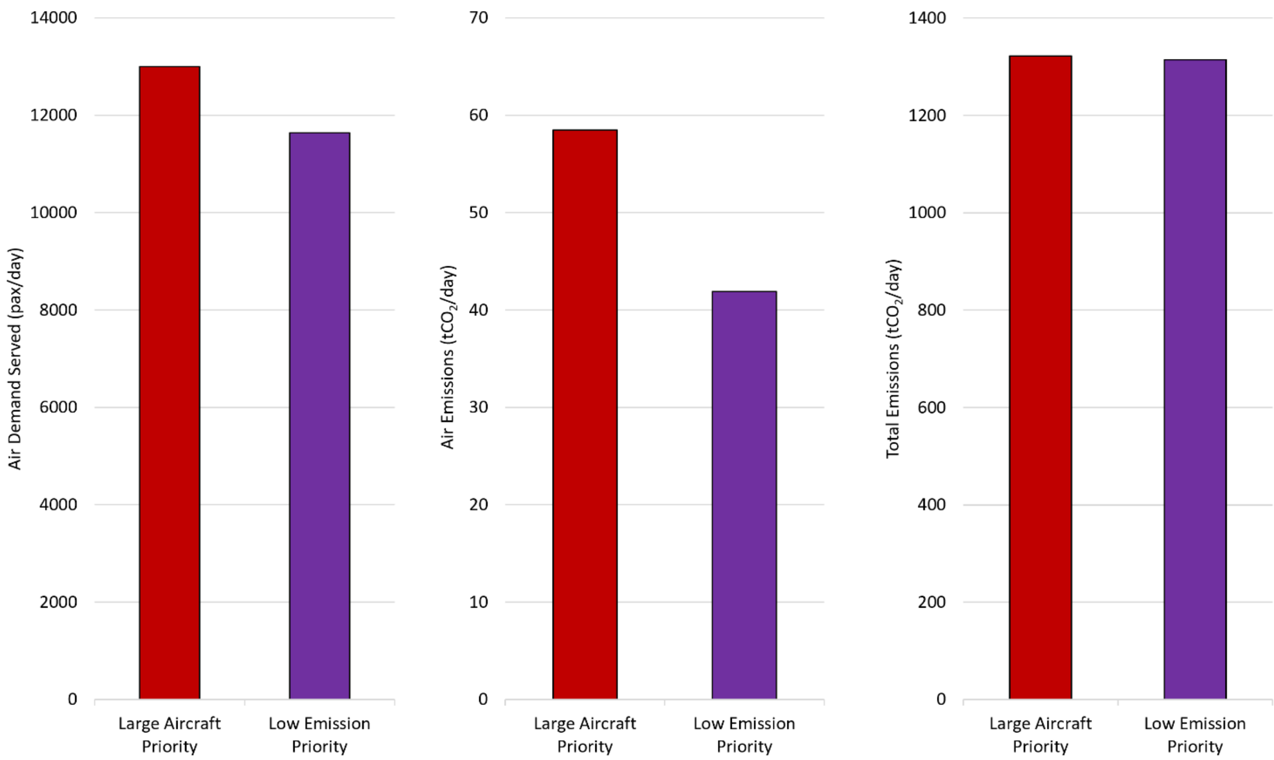

Figure 7: Impact on metrics of prioritizing lowest emission vs. largest available seat category (SAF + Battery + Hydrogen)

6.4 Impact of improving battery technology

In all of the previous analysis, battery powered aircraft were assumed to use batteries with a specific energy density of 400 Wh/kg at the pack level. This specific energy was estimated by assuming a linear progression between 2020 and 2045, which corresponds to what has been observed in the past 30 years [29]. This specific energy density is often considered as what can be expected of a lithium-ion battery in the next 20 years, but it remains very low compared to jet fuel, which is around

13,000 Wh/kg. As a result, aircraft relying only on battery as power source have a range limitation much shorter than current aircraft. But some new battery technology such as lithium-sulfur or lithium-air have theoretical maximum specific energy of respectively 2600 Wh/kg and 11800 Wh/kg at the cell level [30] [31]. In reality reaching 30% of the theoretical maximum specific energy is already a challenging goal, and a much smaller improvement in energy density is more likely if at all possible. To assess the potential of a breakthrough in lithium-ion technology or the introduction of such disruptive new battery technologies, specific energy is increased to 600 Wh/kg in the SAF + Battery + Hydrogen scenario featuring an aircraft assignment strategy prioritizing low emissions. The resulting increase in number of possible flights for the electrified 9 and 19-pax aircraft is depicted in Figure 8. The corresponding impact on metrics is represented in Figure 9.

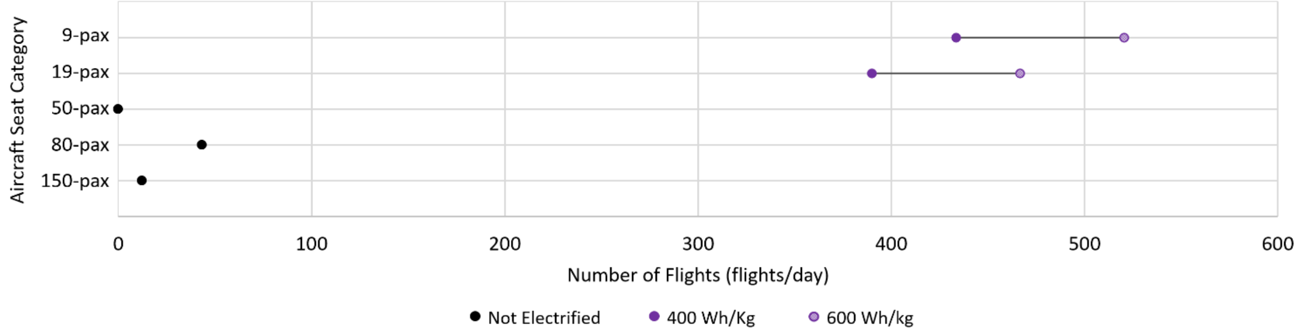

Figure 8: Impact on flights of battery energy density (SAF + Battery + Hydrogen – Low Emission Priority)

The improved battery energy density of 600 Wh/kg allows for longer range of the electric aircraft, and an increase in 13% of air demand that can be served, 24% increase in air emissions, and negligible change in total emissions relative to the 400 Wh/kg case. The serviceable range under stated assumptions improves to 475 km and 320 km for the 9 and 19-pax aircraft, respectively. A similar demand is now served with lower emissions in the 600 Wh/kg case when selecting the most emission efficient aircraft available as compared to the 400 Wh/kg case where large aircraft are prioritized. This demonstrates that with improvements in battery energy density, there is potential for new aircraft assignment strategies to effectively reduce emissions without sacrificing the ability to serve demand.

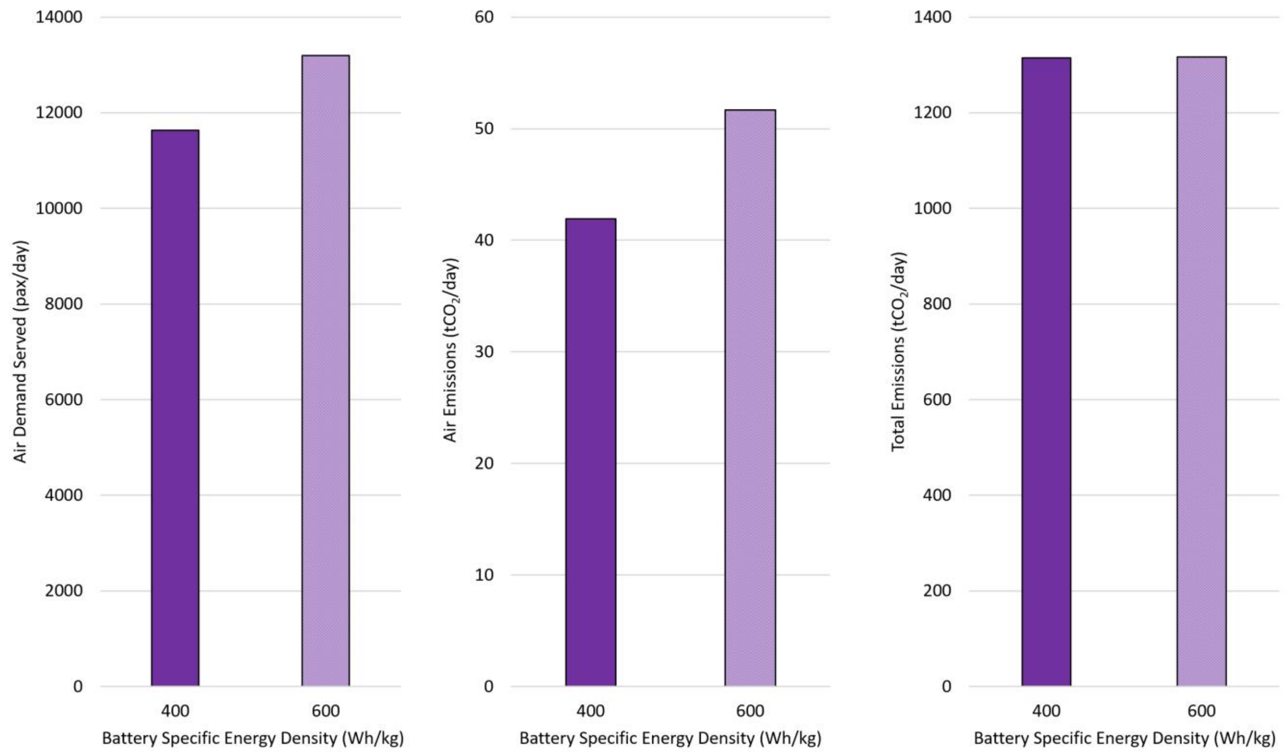

Figure 9: Impact on metrics of battery energy density (SAF + Battery + Hydrogen – Low Emission Priority)

7. Conclusion

A framework for quantifying demand and emissions associated with regional transportation under a variety of future scenarios was created by linking together various analyses with the aim to support decision making. Large demand between underutilized airports was uncovered in Sweden during this assessment, which may compound environmental concerns. This could present an opportunity to support the cost of developing new cleaner regional aviation. Fortunately, modeled operations featuring SAF, battery technology, and hydrogen do show that fuel and energy consumption are within current or projected supply within Sweden and thus significant air emissions reduction can be achieved through the transition to these new technologies. Additionally, a new strategy for aircraft assignment to reduce emissions is presented, and improvements in battery energy density are demonstrated to significantly increase ability to serve air demand. Technology implementations can be confirmed to reduce emissions, however without the exploration of economics and infrastructure, it is not possible to confirm with certainty that zero-emission regional aviation is achievable. Nevertheless, the developed capability can serve as a foundation to build upon for many interesting trade studies to come.

Future work will include economic analysis and will investigate the associated infrastructure requirements for these new technologies. The ability to account for changes in demand and airports used over time as well as an option for passengers to choose between multiple airports would also serve as major additions to the analysis.

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9. Copyright Statement

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