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The Emission Reduction Potentials of First Generation Electric Aircraft (FGEA) in Finland

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Abstract

Under the looming climate crisis, aviation needs to find new solutions to cut its greenhouse gas emissions. One pathway towards zero emissions is the use of electric aircraft. While current battery technology will not allow for medium and long-haul flights at full capacity, on short-haul routes First Generation Electric Aircraft (FGEA) could play a significant role in the near future. Current FGEA under development could carry 9-19 passengers on distances of 400-1046 km by 2025. This study focuses on the emissions reduction potentials of FGEA in Finland. It compares the carbon dioxide equivalent (CO_2-eq) emissions and real travel times (RTT) from door-to-door of FGEA on 47 routes with existing aircraft, train and car transport modes, as well as with proposed high-speed rail (HSR) and electric vehicle implementation. The study found that replacing all existing aircraft with FGEA can clearly be recommended as it would result in a reduction of CO_2-eq emissions and RTT. Existing cars should only be replaced by FGEA on routes beyond 170 km. The replacement of existing trains by FGEA under the current energy mix is not recommended. However, once electricity could be provided from renewable energy sources exclusively, it would become feasible to replace existing trains on distances beyond 170 km and HSR beyond 400 km with FGEA.

Keywords: Modal shift, climate change, greenhouse gas emissions, electric aviation, travel time.

1. Introduction

In response to the climate crisis, the aviation industry has committed to an ambitious goal of carbon neutral growth from 2020 onwards and to half carbon emissions by 2050 based on 2005 figures (ICAO, 2017a). Nevertheless, given the fact that this industry still heavily relies on fossil fuels and is predicted to grow at rates of 6% annually (ICAO, 2017b), this challenge might be larger. Therefore, the industry needs to find new ways to drive emissions down. Solutions that have recently been discussed are mainly around the use of alternative fuels such as biofuels, hydrogen, synthetic fuels, and electricity, as well as hybrid solutions. Given that fully electric aviation appears to be the only pathway to zero emissions, we will exclusively focus on fully electric aircraft design hereafter referred to electric aircraft or electric aviation. Like electric vehicles, electric aircraft could reduce greenhouse gas emissions significantly (Han, Chua & Hyun, 2019) even driving them down to zero in the long run (Gnadt et al., 2019).

While electric aircraft would provide many advantages such as reductions in emissions, noise and operating costs (Reimers, 2018), current battery technology is still not mature enough to supply sufficient power for the most commonly used aircrafts to take-off or flying the same distances as jet fuelled aircraft (Epstein & O'Flarity, 2019). At this stage, electric flying is limited to light aircraft and short design ranges. However, according to Grimme and Jung (2018), it is the short-haul flights that are least efficient, producing twice as much CO_2 emissions per ton kilometre (1653 kg) than long-haul flights (706 kg). Therefore, replacing existing short-haul flights with electric aircraft would appear as a feasible option.

FGEA are currently under development with commercial flights to begin in 2025. Two models especially worth mentioning here are Eviation's Alice designed to carry nine passengers over a distance of 1046 km (Eviation, 2019) and Heart Aerospace's ES-19, a 19-seater with 400 km design range (Heart Aerospace, 2019). While these FGEA would be able to replace existing domestic aircraft such as turboprop and regional jets, they would also directly compete with other land-based transportation modes of a similar range, such as trains or motor vehicles.

The purpose of this paper is to study the emissions reduction potentials of FGEA on short-haul routes. In order to directly compare the emissions of FGEA with existing aircraft, as well as land-based transportation modes, we have chosen to focus on a particular market were the introduction of FGEA is currently under preparation, the case study of Finland. Our study aims to compare the carbon dioxide equivalent emissions of existing modes such as aircraft, train and car with those of FGEA. In addition, we have also added future land-based modes such as electric cars and the proposed Finnish HSR links to the comparison. We took direct emissions created by the modes during the trip as well as indirect emissions from power generation into account. In total we studied 47 city pairs within Finland on which the introduction of electric aviation could be realized. In addition to the CO_2-eq emissions, we also studied door-to-door RTT which has not received much attention in existing literature (Zhao & Yu, 2018).

2. Literature review

Despite electric aircraft being under development and increasingly an important issue within the aviation industry, the topic has received little attention in the literature (Han, Lee, Chua & Kim, 2019; Ratner, Yuri & Hien, 2019). Literature dealing with fully electric aircraft is still very scarce and has only emerged in the recent years. According to Han, Lho, Al-Ansi, Ryu, Park and Kim (2019), electric aviation is broadly understood as an eco-friendly alternative to existing jet fuel-powered aircraft as it does not produce greenhouse gas emissions nor rely on jet fuel. In fact Han, Chua and Hyun (2019) see a great potential in the future of electric aviation in a similar manner to the use of electric cars in road transportation, reducing greenhouse gas emissions significantly. Dominkovic et al. (2018) studied the future transition of the transport sector towards clean energy, considering all alternatives such as electricity, biofuels, hydrogen and synthetic fuels. They found that the use of electricity is showing the best alternative for all transport modes including aviation.

While the use of biofuels in aviation can reduce the lifecycle of CO_2 emissions and hybrid as well as turbo-electric aircraft can reduce the fuel burn and cut overall emissions, only electric aircraft can offer the benefit of achieving zero emissions in the long run (Gnadt et al., 2019). Advantages of electric aircraft are that electric propulsion can achieve higher energy conversion efficiency as there are no thermodynamic efficiency limits, electric motor-ducted fans mainly used in electric aircraft are with scaling size more efficient than gas turbines and electricity powered aircraft would not produce any emissions during flight (Brelje & Martins, 2019; Gnadt et al., 2019). In addition, Brelje and Martins (2019) showed that electricity is on average cheaper than jet fuel so flying electric could also help cut operating costs.

In terms of consumer responses to future electric aircraft, Han, Yu and Kim (2019a) found that for eco-conscious consumers flying electric would appeal as a way of reducing greenhouse gas emissions. However, Han, Yu and Kim (2019b) also see great challenges in the introduction of electric airplanes, which might raise concerns about the safety of this new technology such as explosion risks of batteries, change of performance at different temperatures as well as issues related to battery charging times and battery life times. It is therefore, according to Han, Yu and Kim (2019b), of paramount importance to create trust into the new technology, in order to enhance customer adoption while lowering their perceived risk, by providing more knowledge on the new product.

Despite its many benefits, Dominkovic et al. (2018) also perceive major challenges in the electrification of aviation to be mainly due to the immaturity of technology. The major challenge currently with electric aircraft is the battery technology and its energy density which still restricts the range and the carrying capacity of current designs. Current battery technology would not allow for larger aircraft to be operated fully electric as Gnadt et al. (2019) found, based on their study using an Airbus A320 as a benchmark. According to Caset et al. (2018) to fuel an Airbus A380, the weight of the batteries needed would exceed the maximum take-off weight of the aircraft by 38 times. Epstein and O'Flarity (2019) generate similar results, concluding that electric aircraft will under current technological conditions not be able to significantly contribute to aviation's emissions reductions in the first half of this century. According to Epstein and O'Flarity (2019), 92% of the current aircraft globally could not be able to even take-off or operate currently flown ranges based on the available battery technology, whilst most greenhouse gases produced by larger aircraft on longer routes could not be substituted any time soon by electric aircraft. At this moment, only small aircraft could be fully electric. As Gnadt et al. (2019) demonstrated, over the past decade more than 70 electric aircraft models have been studied and developed. However, these were mainly light aircraft with short design ranges.

This review has shown that there is potential for electric aviation in niche markets that use smaller aircraft over shorter distances. However, this potential could grow with technology developments and overcoming consumer concerns.

3. Background

The Nordic countries have taken a forerunner role in electric aviation with the foundation of the Nordic Network on Electric Aviation (NEA), which consists of the major Nordic airlines of SAS, Finnair and Icelandair, as well as airport operators and other major players. The aim of NEA is to reduce carbon emissions of regional aviation significantly and to put the Nordic countries into a leadership position on the transition to electric regional aviation. The goals are hereby ambitious as Norway aims for all short-haul flights to be 100% electric by 2040 (The Guardian, 2018), while Sweden wants to have all domestic air travel to be fossil-fuel free by 2030 (Fossil Free Sweden, 2019). With Heart Aerospace and Rolls-Royce Electric Norway, there are already major manufacturers of electric aircraft and engines located in the Nordic region. That Nordic consumers have become more sensible to the climate impacts caused by flying shows the "Flight Shaming" movement that began in Sweden which, according to latest studies, could further spread and significantly slow the growth of the aviation industry (BBC, 2019). It is, therefore, important for the aviation industry to come up with new solutions how to reduce its carbon footprint. The implementation of FGEA could hereby be seen as one feasible solution. FGEA provide many advantages over existing aircraft, however, show also certain limitations, as shown in Table 1.

Table 1. Advantages and disadvantages of FGEA (Reimers, 2018)

Advantages	Disadvantages
+ Reduced emissions	- Shorter range
+ Reduced energy consumption	- Lower seating capacity
+ Noise reduction	- Battery safety issues
+ Short-field operations	- Battery charging time
+ Reduced maintenance and operation costs	

Finland has ambitious plans to introduce FGEA on domestic routes as soon as 2025 (Helsinki Electric Aviation Association, 2019). Finland is defined by long distances and a low population density. Despite its small population of 5.5 million, Finland operates an extensive domestic flight network. Currently there are 17 domestic routes connecting the countries major cities with the capital Helsinki. Although the market share of domestic aviation in Finland is only at 0.1%, aviation is responsible for 2.4% of the transport sector's total CO_2 emissions (Baumeister, 2019). In addition, a recent study determined that Finns are the second highest emitters (per capita) of CO_2 from aviation and that domestic flying has a relevant share of that figure (Yle, 2019). While Finland depends on domestic aviation, especially to reach far out destinations within a reasonable travel time, it needs to address its aviation-related emissions. According to Baumeister (2019), existing land-based transportation modes in Finland can keep up with the travel times of aircraft on distances up to 400 km. However, beyond this they tend to be significantly slower. Here the use of electric aircraft could be one solution.

Due to the advantage of short-field operations, as well as the fact that FGEA are limited in seat capacity, electric aircraft could also operate from smaller airports within Finland that are currently not served by existing airlines. By reviewing all existing airports and airfields in Finland, we were able to identify 30 additional airports that are currently not served, adding the total amount of airports studied to 47. Additional airports under consideration have asphalt runways of a sufficient length, and a population of at least 10 000 inhabitants or were otherwise attractive tourist destinations.

While currently existing flights are all operated out of Finland's major hub Helsinki Vantaa Airport, Helsinki Electric Aviation Association (2019) sees Helsinki Malmi Airport as a more suitable alternative to operate electric flights in and out of Helsinki. Malmi Airport served as Helsinki's major airport until the opening of Helsinki Vantaa in 1952 and is currently mainly used for general aviation. In addition to domestic short-haul flights, 32 of these cities that could be served by electric aviation are also directly connected with Helsinki by rail. There are also road connections to 46 of these cities from the capital of Helsinki. In addition, there are plans to build two new high-speed rail links from Helsinki to Turku and Tampere, which would have a direct impact on the travel times on 13 of the 28 routes connected by rail, reducing travel times by 30-60 minutes (One Hour Train, 2019; Finland Railway, 2019).

4. Calculations

Following IPCC's guidelines in the Fifth Assessment Report (IPCC, 2014) for the climate impact of local emissions, CO_2-eq emissions were calculated based on the following formula:

$$CO_2\text{-eq} = CO_2 + CH_4 * 28 + N_2O * 265 \qquad (1)$$

The time frame chosen for the Global Warming Potential for this study was 100 years (GWP_{100}).

4.1 Aircraft

Currently, the most commonly used aircraft type on domestic flights in Finland is the ATR72 turboprop aircraft operated by Nordic Regional Airlines (Norra) on behalf of Finnair. Finnair also uses aircraft of the Airbus A320-family on longer routes to Oulu and to the airports in Lapland which are Rovaniemi, Kittilä and Ivalo. Most airports receive only 2-3 flights per day. The only exceptions are Joensuu with four daily flights, Vaasa and Rovaniemi with five, Kuopio with six flights and Oulu with fifteen flights. Schedules and flight times were taken from Finnair's 2019 summer timetable. Fuel consumption based on the Great Circle Distance were estimated using the EMEP/EEA Air Pollutant Emissions Inventory Guidebook (EEA, 2019). CO_2 emissions were calculated by multiplying the fuel burned by 3.169, which equals to the amount of CO_2 produced when burning 1 kg of aviation fuel (VTT, 2017). For calculating the CH_4 and N_2O emissions, 0.0005 g/MJ and 0.002 g/MJ were assumed while the heat value of the fuel in MJ was determined with 43 MJ/kg of fuel based on VTT (2017). Finally, in order to allocate the emissions per passenger, the standard configuration used with 72 seats (ATR 72) or 158 seats (A320) and a 62% load factor as, according to the Finnish Transport Agency (2015), common for flights within Finland were assumed.

In terms of the future use of electric aircraft in Finland from 2025 onwards, two aircraft models have been identified by Helsinki Electric Aviation Association (2019) that suit the needs of the Finnish market. These are the Eviation's 9-seater Alice and Heart Aerospace's 19-seater ES-19. Both aircraft types are fully electric and will be certified and ready for commercial use in 2025. Table 2 shows both aircraft's technical specifications.

Table 2. Electric aircraft technical specifications (Eviation, 2019; Heart Aerospace, 2019)

Model	Passengers	Range	Battery power	kWh/pkm[1]
Eviation Alice	9	1046 km	900 kWh	0.154
Heart Aerospace ES-19	19	400 km	575 kWh	0.122

[1] 62% load factor

The energy consumption per passenger kilometre (pkm) shown in Table 2 are in line with Reimers (2018). The CO_2-eq emissions for producing the electricity consumed during electric flights was calculated based on the existing energy mix of Finland. According to Statistics Finland (2019a), in 2018 the Finnish energy sector produced 67 TWh of electricity which resulted in a release of 42.4 million t of CO_2-eq emissions (Statistic Finland, 2019b) or 633 g CO_2-eq per kWh. This is in line with the average for OECD countries, as discussed in Hoelzen et al. (2019). Flight times were estimated on the EMEP/EEA Air Pollutant Emissions Inventory Guidebook (EEA, 2019), which used the ATR72 aircraft as a reference model which is flying on similar speed and flight levels than the two proposed FGEA. For our calculations we assumed the use of the more energy efficient Heart Aerospace ES-19 on routes up to 400 km, while on flights beyond we based our calculations on Eviation Alice that can also reach the most remote airports in Lapland.

Both for existing aircraft and electric aircraft, access time to the domestic airports and downtown Helsinki, as well as the produced CO_2-eq emissions, were estimated. For reaching domestic airports, the use of private car or taxi was assumed, which is the most common practice in Finland. For reaching downtown Helsinki from Vantaa Airport, the use of the airport train (FLIRT/Sm5 electric-multiple unit) was estimated as the most feasible option. For the transfer from Malmi Airport, we assumed the introduction of a new direct (electric) bus line. Driving time and distance were extracted from Google Maps. Energy consumption was taken from the Libasto Unit Emissions Database (VTT, 2017) and the CO_2-eq emissions for energy production were based on the Finnish energy mix described above.

In addition to the travel times to and from the airports, we also added time spend at the airport to the RTT of flights. In the case of existing air travel, check-in for all flights closed 45 minutes prior to departure. We added, therefore, 30 minutes of time prior to the closure of check-in to RTT, as well as 45 minutes for clearing security, arriving at the departure gate and boarding which usually begins 25 minutes prior to the scheduled departure. After the scheduled arrival time in Helsinki we added 40 minutes for the transfer from the aircraft to the airport train, including time to claim baggage, buying tickets for the train and waiting time for the next train. For reaching downtown Helsinki, 31 minutes were added to the RTT, which is the actual travel time of the airport train.

In the case of the electric aircraft which will operate from much smaller airports and airfields, less time had to be allocated at airports. In addition, due to the much smaller passenger numbers of 9-19, less time is required for security control and boarding. Here only 40 minutes was allocated for the time between arrival at the airport and the scheduled aircraft departure. For the transfer from the aircraft to the connecting bus to downtown Helsinki only 20 minutes was estimated, due to the much smaller facilities at Helsinki Malmi Airport. For bus transfer to downtown Helsinki 30 minutes was added to the RTT.

4.2 Train

Rail transport in Finland is operated by state-owned Finnish Railways (VR), which serves 32 out of the 47 routes studied with existing non-high-speed rail (NHSR) trains. Most routes are served by doubledecker push-pull InterCity trains that can run on top speeds of up to 200 km/h. In addition, on some branch lines, including the airport train to Vantaa Airport, different types of electric-multiple units commuter trains are used. Energy consumption of these different train types have been extracted from the Libasto database (VTT, 2017). All electric trains in Finland run on hydropower. The CO_2 and CH_4 emissions per kWh were calculated based on Hertwich (2013). N_2O emissions were not considered as they are relatively minor in boreal regions such as Finland (Hertwich, 2013). In addition, on some route diesel driven Rail Cars are used. The CO_2-eq emissions for these journeys were calculated based on the Libasto database (VTT, 2017). Travel times were taken from VR's 2019 summer timetable. In addition to the scheduled travel time 10 minutes were added to the RTT of trains in order to allocate for passengers to arrive at the station on time to find the right platform and board the trains safely.

In order to upgrade the existing railway network and to provide faster connections between the major growth centres of Finland, the introduction of two HSR corridors is currently planned. The lines should allow Tampere and Turku to be reached from Helsinki within one hour (Finland Railway, 2019; One Hour Train, 2019). Therefore, to represent the development of HSR in our study we have discounted the RTT for the 17 routes that would see direct effects from the HSR lines down to one hour between Helsinki and Tampere/Turku. In order to account for the higher energy consumption due to running trains at higher speeds we have assumed 0.097 kWh/pkm (at 40% load factor) which is regarded a good average for HSR according to Prussi and Lonza (2018). In terms of route length we have reduced the distance to Turku by 40 km in accordance with the planned new line (One Hour Train, 2019) while we didn't change the distance to Tampere as the HSR line is planned to follow the existing tracks (Finland Railway, 2019).

4.3 Car

It is common to travel by car over long distances in Finland. We have therefore also studied the use of car on 46 routes, only leaving out Mariehamn which is not connected by road with Helsinki. Distance and travel time were determined by Google Maps. Emissions were calculated based on the Libasto database (VTT, 2017) assuming an average car occupancy for Finland of 1.9 passengers for highway and 1.3 for urban driving, whilst the share of diesel car mileage was estimated at 41%. In addition, we also studied the use of electric cars (E-Car). Energy consumption was as well extracted from the Libasto database, whilst the CO_2-eq emissions for energy production were based on the Finnish energy mix.

Table 3 provides an overview of emissions per pkm for the different transport modes studied.

Table 3. Emission per pkm

Mode	Specifications	Load Factor	g CO_2-eq/pkm
Aircraft	Jet engine, Airbus A320	62%	185.76
	Turboprop, ATR72	62%	146.58
FGEA	Electric, Heart Aerospace ES-19	62%	77.23
	Electric, Eviation Alice	62%	97.48
NHSR	Electric, InterCity/Sr2 locomotive-hauled	40%	9.13
	Electric, FLIRT/Sm5 electric-multiple unit	35%	12.00
	Electric, Sm4 electric-multiple unit	35%	14.37
	Diesel, Dm12 Rail Car	35%	76.43
HSR	Electric, non-specific	40%	16.39
Car	Gasoline/Diesel, non-specific, highway	38%	69.35
	Gasoline/Diesel, non-specific, urban driving	26%	156.46
E-Car	Electric, non-specific, highway	38%	69.63
Bus	Electric, non-specific, urban driving	42%	49.37

5. Results

When comparing the CO_2-eq emissions per passenger of the ATR72 currently in use with the proposed electric aircraft, as shown in Figure 1, there is a significant emissions reduction potential.

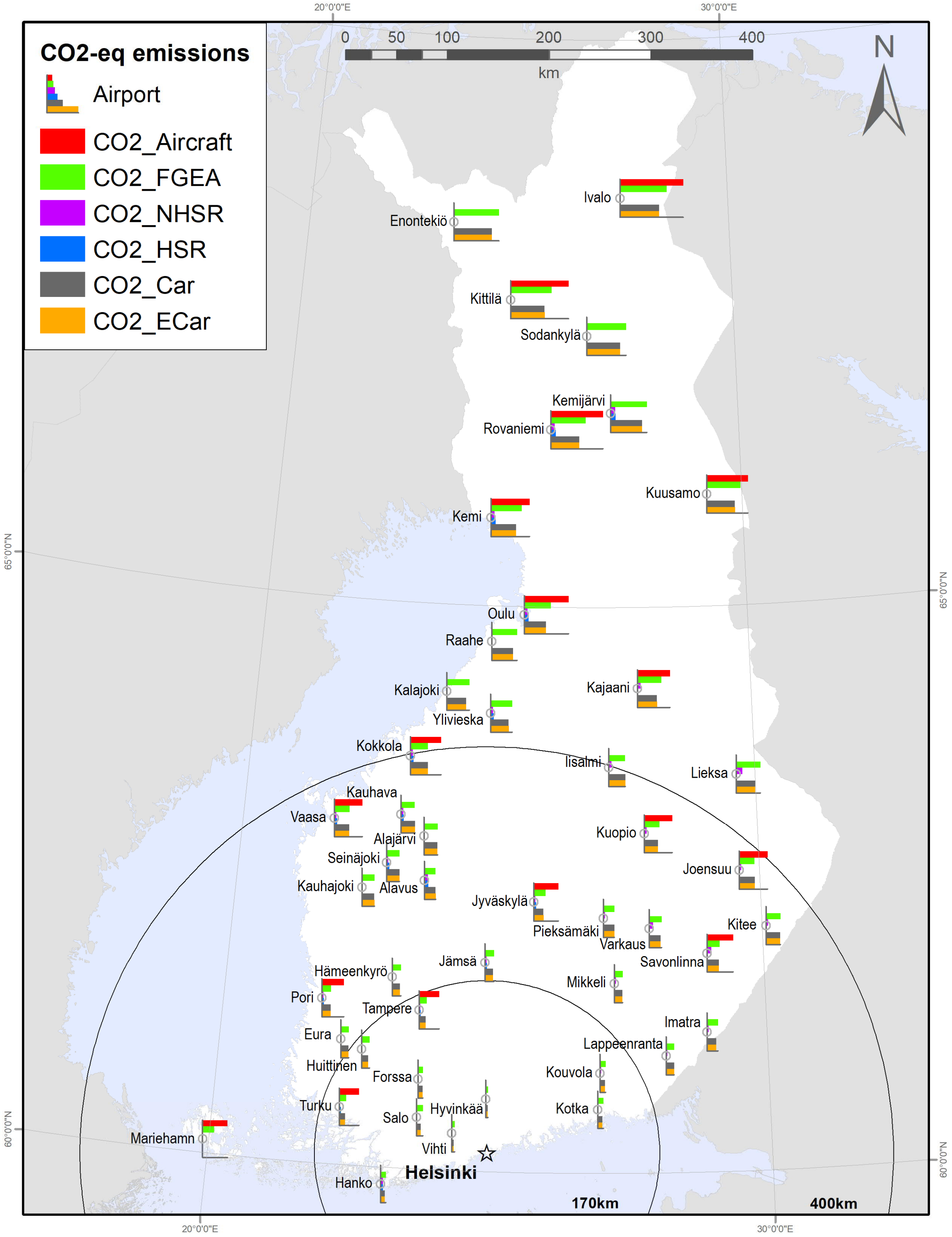

Fig. 1. kg CO_2-eq emissions per passenger for all 47 city pairs

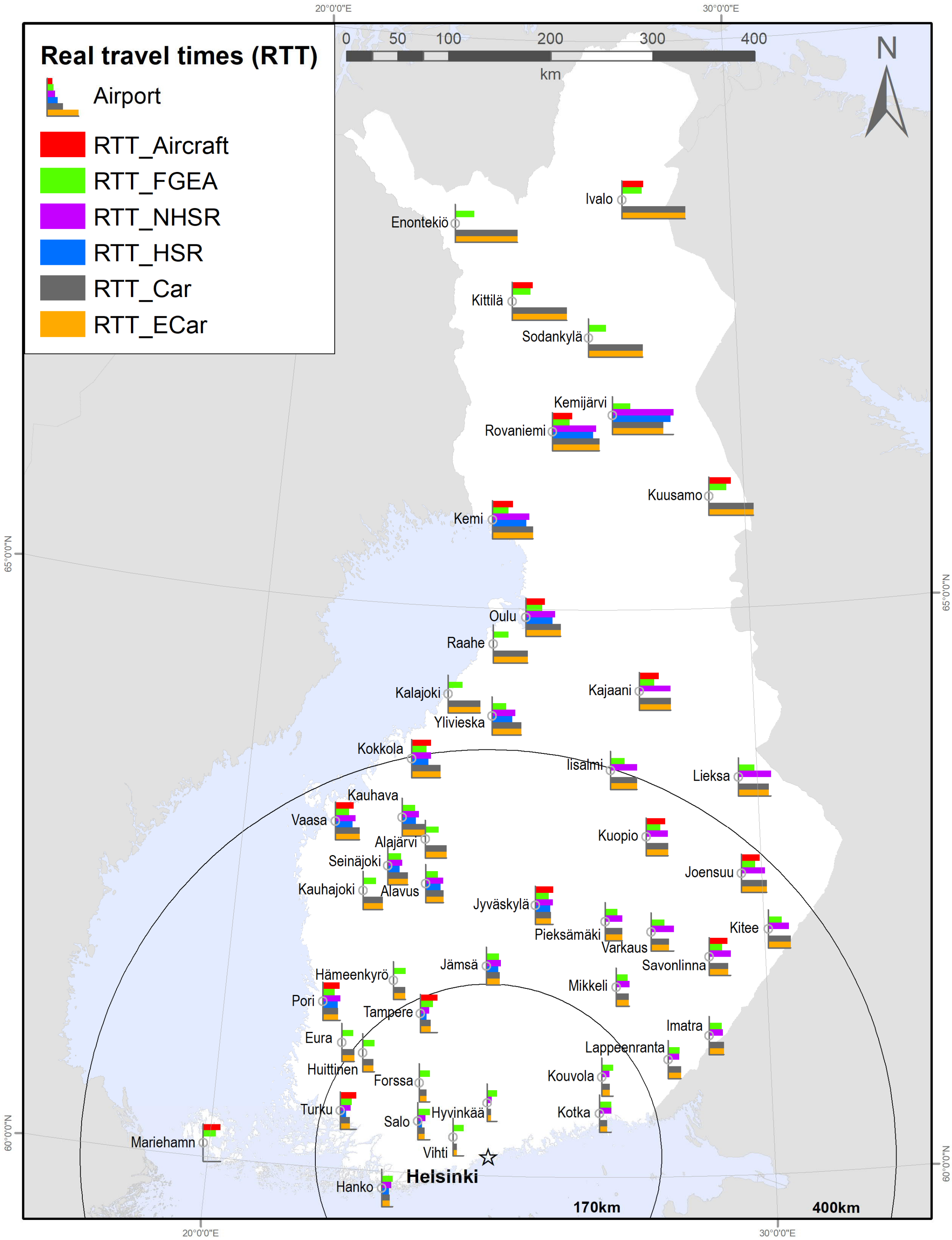

Fig. 2. Comparison of RTTs for all 47 city pairs

In terms of shorter routes where the ATR72 is the least efficient, CO_2-eq emissions reductions can be up to 64% as in the case of flights to Turku, while they start to decrease with increasing route length and do only account for 43% in case of flights to Kokkola, the longest route that could be flown by the more efficient Heart Aerospace ES-19. On routes beyond 400 km were Eviation Alice be used, the emissions reductions compared to the ATR72 are down to 21% as in the case of flights to Kemi. However, on routes where the A320 is used, Eviation Alice could again cut emissions significantly, almost 40% in the case of Oulu. Replacing existing aircraft with FGEA on shorter routes, where existing aircraft such as the ATR72 cannot operate on their optimum, would certainly be sensible. On longer routes towards the maximum range of FGEA a replacement would still be reasionable although the efficiency gains are less. Nevertheless, when comparing the FGEA with the CO_2-eq emissions of NHSR, existing trains are between 84-90% more efficient depending on the route. Only on routes were parts of the trip have to be completed by diesel driven Rail Cars, does the efficiency drops to between 58-74%. In addition, the slight increase in energy consumption in the case of HSR does not significantly change these numbers, only decreasing the efficiency of rail compared to FGEA by 2-9%, depending on the route. Here the train has a clear advantage, as it is mainly run on renewable energy sources, whilst the FGEA would still heavily rely on electricity produced from mainly fossil fuels.

Once more electricity from renewable sources become available, the emissions produced from electric aviation would drop significantly, reaching those of the train and eventually zero. The same also accounts for the surprising finding that E-cars under the current Finnish energy mix would produce 0.46% more CO_2-eq emissions than the existing average car used in Finland. In terms of CO_2-eq emissions, and with increasing distance, the more efficient Heart Aerospace ES-19 achieves similar values as existing cars and E-cars, even showing lower emissions on some routes. On routes where Eviation Alice would be used, however, CO_2-eq emissions are 15-22% higher than those of cars.

In regard to RTT, and as shown in Figure 2, the FGEA clearly outperform existing aircraft, which can be explained by its leaner operations, fewer passengers and the use of the much smaller Helsinki Malmi Airport. While FGEA would operate at the speed of current ATR72, they could even outperform faster flying jet aircraft on the longer routes to Oulu, Rovaniemi, Kittilä and Ivalo due to their leaner operations. When comparing RTT of electric aviation with ground-based transportation modes, it shows that for distances up to 170 km ground transportation outperforms the electric aircraft clearly. Beyond 170 km, and with increasing distances possible, electric aircraft provide a faster link to downtown Helsinki compared to NHSR and car use. Nevertheless, introducing HSR on the section between Helsinki, Turku and Tampere would help the train achieve RTT similar to that of the FGEA, at least on routes up to 400 km.

6. Discussion & Conclusion

This paper set out to study the emissions reduction potentials of FGEA on short-haul routes, using Finland as an example where the introduction of FGEA is currently under preparation. In addition to CO_2-eq emissions, RTT was also considered. The results demonstrate that FGEA would outperform current aircraft both in terms of emissions and RTT. Therefore, the replacement of existing aircraft with FGEA should be recommended. FGEA could hereby provide an effective alternative to existing short-haul flights which are, according to Grimme and Jung (2018), the least efficient in terms of emissions per ton kilometre.

Besides savings in emissions and RTT, FGEA could also provide other benefits to domestic aviation, as shown by the example of Finland. The restrictions of FGEA in capacity and range limited by the currently available battery technology is at the same time also its greatest advantage. Due to the smaller size, FGEA could provide service to smaller airports that are not currently served by existing aircraft. In the case of Finland, up to 30 additional airports were identified. FGEA could make quicker links between the capital and smaller cities and towns that are not very well connected by rail or road. These include those with no existing connections. While smaller aircraft size might require a greater frequency, it would also add more flexibility to travellers as more flights would be offered per day.

Thinner routes with only 2-3 daily flights currently to the capital would particularly benefit from FGEA. Bussier routes, such as to Oulu, could also have more frequent daily flights, given that flights to Helsinki could take off every 30 minutes. With advances in battery technology and increasing aircraft size, some of these advantages might naturally decrease over time. Finally, another advantage of electric aviation is the significant reduction in noise compared to existing aircraft. On the other hand, there are also challenges FGEA will encounter and need to overcome, such as the issue related to battery safety and charging times. Nevertheless, as this study showed, by replacing current inefficient short-haul flights, FGEA could become the forerunners of the decarbonisation of the aviation industry aiming at zero emissions.

While the replacement of existing aircraft with FGEA on short-haul routes can clearly be recommended, the situation with land-based transportation modes is different. In comparison with cars, FGEA show higher CO_2-eq emissions and longer RTT on routes up to 170 km. However, beyond 170 km FGEA's emissions start to become closer to those of cars, even outperforming them on some routes. Only beyond 400 km, where the less efficient Eviation Alice would be used, cars again show lower CO_2-eq emissions. However, in turn RTT of FGEA would be significantly lower than those of cars. Therefore, it could be recommended to replace car travel on routes beyond 170 km with FGEA due to the significant time saving potentials, paired with only a slight but acceptable increase in emissions. The replacement of existing cars with E-cars under the current energy mix would not be recommended. In comparison with car travel, FGEA could provide a feasible alternative, as FGEA are almost capable of closing the gap between emissions produced by cars and aircraft but could provide significant RTT savings.

In a similar way to cars, the RTTs of NHSR are less favourable on distances beyond 170 km compared to FGEA. The introduction of HSR could, however, push this boundary up to 400 km. Nevertheless, when taking the emissions into account, replacing NHSR with FGEA cannot be recommended as CO_2-eq emissions of FGEA, under the current energy mix, are significantly higher than those of trains. Only with the consequent change of the energy mix in Finland, discontinuing the burning of coal, peat and wood-based fuels, and replacing them with renewable energy sources, could significant emissions reductions be achieved that would justify the replacement of trains with electric aircraft. This also accounts for the replacement of existing cars with E-cars. Our findings are hereby in line with Epstein and O'Flarity (2019), who show that current jet engines produce in fact less CO_2 per kWh than the average grid and this is not projected to change within the next 25 years.

We conclude that in order for electric mobility to become a real alternative to the highly carbon-constrained transportation system currently in place, and to achieve the transition towards zero emissions, the shift to renewable energy sources is unavoidable. Electric trains, as an example, currently run in Finland on hydropower, showed by far the lowest CO_2-eq emissions of all modes covered in this study. In addition, the electrification of transportation would also increase the demand for electricity which could not be satisfied with existing production methods. According to Epstein and O'Flarity (2019), if all commercial aviation would be electrified, the world electricity production also would need to be increase by 26%.

In terms of limitations, our paper did not take into consideration emissions created by building and maintaining infrastructure for the different transportation modes studied. In particular, there is the opening of 30 additional airports for passenger service of FGEA operations or building HSR corridors to Tampere and Turku, which presents a significant increase in emissions. The emissions created by airport infrastructure alone, for example, can be quite significant, as shown by Schmidt et al. (2016). In addition to that, our study only compared the CO_2-eq emissions of different transportation modes, not taking into account the effect of contrail-cirrus clouds that are produced by existing aircraft.

Contrail-cirrus clouds can have about the same magnitude of radiative forcing than CO_2 emissions while electric aircraft do not combust fuel and therefore not emit water vapour at high-altitudes (Avila, Sherry & Thompson, 2019; Gnadt et al., 2019). If considering this, the shift from existing aircraft to FGEA could reduce climate impacts even more than estimated in our study. In addition, our paper has not discussed other environmental benefits of FGEA compared to existing aircraft, such as significant reductions in local air pollution and aircraft noise around airports, which could be a subject for further research.

Finally, our study expanded previous work by Baumeister (2019) which looked into the replacement of short-haul flights with existing land-based transportation modes in Finland. Baumeister (2019) found that based on CO_2-eq emissions all short-haul flights should be replaced by land-based modes while in terms of RTT this would only be feasible on distances up to 400 km. With this study we were able to show that short-haul flights in form of FGEA can be a sustainable alternative to land-based modes, as long as the electricity is supplied by renewable energy sources.

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