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Low-carbon scenarios for long-distance travel 2060

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ABSTRACT

In many industrialised countries, the climate impact from long-distance travel is greater than that from short-distance travel. In this paper, we present five scenarios for long-distance travel in 2060, which are consistent with a 67% probability of limiting global warming to 1.8 degrees. The scenarios concern travel by the Swedish population, but per capita travel volume and fuel use could be generalised globally. A key result is that all scenarios require reductions in Swedish per capita air travel in the range of 38–59% compared to 2017. The direct effect on air travel of implementing a high-speed rail network in Sweden and Northern Europe was found to be modest. A higher emission reduction could be achieved if mixed mode trips comprising rail and air legs were more widely adopted. Finally, the pros and cons of future aviation fuels are discussed, the main candidates being biofuel, electrofuel, and liquid hydrogen.

1. Introduction

Limiting global warming to between 1.5 and 2 degrees, as agreed in Paris in 2015, requires substantial transformations in all sectors of society. In many high-income countries, long-distance travel has a larger climate impact than short-distance travel (Van Goeverden et al., 2016; Larsson et al., 2018). In this paper, long-distance travel is defined as trips that exceed 100 km one way. Aviation, which is the major emitter in this segment, generated 2.4% of the global anthropogenic CO_2 emissions in 2017 including land use change effects (Lee et al., 2021). In addition, under some atmospheric conditions, high-altitude emissions of water vapour may form contrails and cirrus clouds, which on average have a warming effect. The exact level of these and other non-CO_2 effects is uncertain, but the best available scientific estimates indicate that the total warming effect of aviation is 1.7 times as high as that of CO_2 alone, measured as GWP100 (i.e. Global Warming Potential with a 100 year horizon) (Lee et al., 2021). If a shorter time perspective were used due to the risk of triggering natural positive feedback loops in the climate system, then this factor would be higher, for instance a 50 year time horizon would give a factor of 2.3 (ibid). In this paper, we use the factor 1.7 for multiplying CO_2 emissions to get the total climate impact. For high-income countries aviation emissions constitute a significant share, for instance, total air travel by the Swedish population in 2017 accounted for 13.6% of total consumption based greenhouse gas (GHG) emissions (Larsson et al., 2018; Naturvårdsverket, 2021).

Long-distance travel will struggle to meet the climate targets. Shepherd et al. (2019) found that even with slow economic development and an advanced application of transport policy, European long-distance travel would be far from meeting the previous

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2050 EU-target of −60% compared to 1990. With the newly updated stronger EU climate policy, targets would be even more difficult to reach. The IEA estimates that emissions from aviation could be reduced by 60% to 2030, but that this would require significant behavioural changes (Cozzi et al., 2020).

In this paper a backcasting approach is used to explore future long-distance travel which entails identifying futures reaching the targets and analysing how to get there.

Most previous backcasting studies of the transport system focus on short-distance travel while long-distance travel is usually less elaborated on. Studies focusing more closely on how long-distance travel can meet stringent climate targets are few, notably Ceron and Dubois (2007), Peeters and Dubois (2010), Dubois et al. (2011) and Peeters et al. (2019). There are also studies focusing specifically on aviation like Åkerman (2005), the Committee on Climate Change (2009), Becken and Carmignani (2020) and Sharmina et al. (2020).

The aims of this paper are to: (1) identify possible long-distance travel futures that are in line with the Paris agreement, including estimating the feasible amount of air travel, with Sweden as a case; (2) explore the challenges in realising each of these futures; and (3) analyse how decisions in the present could turn the development in a direction indicated by the scenariosA key contribution of the paper is thus to analyse what levels of long-distance travel, and in particular air travel, that are consistent with achieving the climate targets given various technological developments and behavioural changes. This paper concerns long-distance travel by the Swedish population. However, the scenarios and conclusions may also be applicable to other Western European countries having the same magnitude of long-distance travel, although with some adjustments related to specific geographical circumstances. Long-distance travel by the Swedish population, measured as passenger-km (pkm), and its associated GHG emissions are shown in Table 1 by mode of travel. The Swedish air travel of 5800 km/cap in 2017 may be compared with a study by Christensen (2016) which found that air travel by Danes in 2010 amounted to 5700 km per capita and a study by Aamaas and Peters (2017) which found that Norwegians flew 5300 km per capita in 2009. The Swedish air travel volume is nearly six times higher than the global average of about 1000 pkm per capita and year (ICAO, 2018; World Bank, 2021).

In section 2 the overarching methodological approach of the paper is described, including the reasoning behind the targets for GHG emissions that are used for the scenarios. The key measures to reduce the climate impact of long-distance travel are elaborated on in Section 3. Particular emphasis is put on the potential to shift travel from air to rail. The scenarios are then presented and analysed in Section 4. Section 5 contains a discussion about key aspects and uncertainties with regard to the scenarios and their target fulfilment. Finally, conclusions are drawn in Section 6.

2. Methodological approach

The approach used in this paper is one of several variants of backcasting. A central part of backcasting is designing "images of the future" that reach set-up targets for a specific system. An early backcasting approach outlined by John Robinson (1982) included moving step by step back in time from the "images of the future" to the present. However, since the future will bring surprises, we do not find it credible to describe a detailed path between the present and a future state. Nevertheless, outlining consistent futures can provide an important input for decisions in the present, in particular those that have long-term consequences. Regarding long-distance travel, examples of such decisions are choices of future air transport fuels, potential introductions of novel aircraft configurations (e.g. open rotor), and investments in new infrastructure like high-speed rail (HSR) networks. In Höjer et al. (2011), four variants of backcasting are described. The kind that we use in this paper is similar to the type called "target-oriented backcasting", although here we focus more on near-term strategic decisions (Åkerman, 2011).

Although "image of the future" is a commonly used term in backcasting studies, we will in this paper use the term "Scenario" both regarding the future state in 2060 and the development from now till then. In this study, five scenarios are explored based on different key features, where some scenarios rely more on technological solutions while other scenarios entail larger shifts in travel patterns. Scenarios 1–4 are each focused around a rather disruptive shift regarding one of the measures covered in section 3, although other measures are also applied to a lesser extent. Scenario 5, on the contrary, applies incremental improvements for a wider range of measures. All scenarios are designed to reach the climate targets. The main measures analysed in Section 3 are:

1. Modal shift from air to modes of transport with lower emissions
2. Reduced specific energy use through more efficient vehicles and increased occupancy
3. Low-carbon fuels
4. Improved organisation of air traffic

Table 1
Travel volumes and GHG emissions generated by the Swedish population's long-distance travel in 2017.

	Long-distance travel (pkm/cap)	Specific emissions (kg CO_2.eq./pkm)	Emissions (kg CO_2.eq./cap)	Share	Sources
Air	5 800	0.152	905	81%	Kamb and Larsson (2019)
Car	2 100	0.094	197	18%	Trafikanalys (2020a); Trafikverket (2019)
Rail	690	0.004	3	<1%	Trafikanalys (2019); Åkerman (2012) and own calculations
Coach	150	0.020	3	<1%	Trafikanalys (2020a); Åkerman (2012) and own calculations
Ferry	55	0.170	9	<1%	Åkerman (2012) and own calculations
Total	8 795		1 116		

5. Limited total long-distance travel volume

2.1. Climate targets for long-distance travel

The point of departure is the Paris Agreement and the target used in this paper is an 85% reduction by 2060 of the gross GHG emissions which were 49.2 Gt in 2017 (UNEP, 2018). This is broadly in line with the Sustainable Development Scenario outlined by the IEA (2020), which is stated to have a 67% likelihood of limiting global warming to 1.8 degrees. With present global population projections pointing to around 9.9 billion people by 2060 (UN, 2019), this target translates to global per capita emissions of 0.75 tonnes of CO2-eq. per year in 2060.

A key question is how much of these 0.75 tonnes that should be allocated to long-distance travel. Currently, 13.6% of the 8.15 tonnes of CO2-eq. from consumption based Swedish emissions (Naturvårdsverket, 2021) stems from long-distance travel (Table 1).

There are arguments for long-distance travel both decreasing and increasing its share of total emissions. Within the transport sector aviation is one of the hardest to decarbonize. On the other hand, there are sectors like agriculture where it may be even more difficult to reduce emissions. It is a fact that aviation is largely exempted from climate taxes and VAT that are levied on road transport at least in most developed countries. Abolishing these exemptions would enable a faster reduction of emissions in this sector. Since air travel is not a basic good it's share of emissions is generally positively correlated with income levels, that is, when developing countries get more affluent the share of emissions from long-distance travel tend to increase. The future share of total emissions from long-distance travel is thus dependent on several drivers. Here it is assumed in the scenarios that the share for Swedish residents is unchanged at 13.6%, and that the share globally also reaches this share towards 2060, mainly due to expected increasing incomes globally. We acknowledge the large uncertainty by calculating the air travel volumes at a lower share, 10%, and a higher share, 17% (see Fig. 4 in Section 5). It is important to note that the distributional assumption underlying all scenarios is that the average Swedish air travel per capita will have converged with the global average in 2060. The emissions from long-distance travel for 2017 are estimated to 1116 kg CO2-eq. per capita (GWP100) and the scenarios are designed to meet the targets, which are 575 kg CO2-eq. per capita by 2040 and 102 kg by 2060.

3. Measures to reduce climate impact from long-distance travel

In this section, we elaborate on the potential of key measures to reduce the climate impact of long-distance travel. Regarding modal shift, we present novel results from an analysis based on the Swedish national travel survey for 2017 (SCB, 2018). The survey was sent to 60,000 individuals and had a response rate of 30%. Both business travel and private travel were covered in the survey and it included 2967 trips made by air (unweighted – in the calculations data is weighted to represent the Swedish population). The other ways of reducing emissions are based on reviews of state-of-the-art. The focus is on air travel since this mode accounts for more than 80% of the emissions from long-distance travel but other modes are also considered.

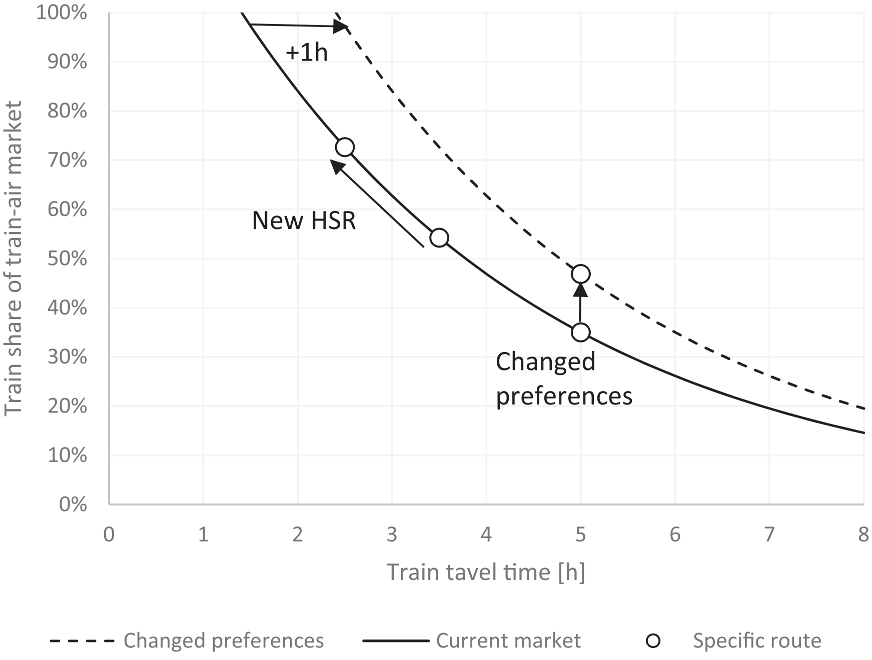

Fig. 1. Rail travel's market share as a function of travel time by rail, in the rail and air market. The dashed line indicates how the market share would shift if people accepted one hour longer travel times. The solid line is adapted from Lundberg (2011) and Nelldal and Andersson (2012).

3.1. Modal shift

The main potential for reducing GHG emissions from modal shift is by replacing air travel with other modes of travel. Obviously, the possibility to travel intercontinentally by surface transport is very limited, but within Europe rail travel could, at least theoretically, replace virtually all air travel. However, such modal shifts depend to a large extent on the rail travel time to the destination, while factors such as frequency and price have less importance (Dobruszkes et al., 2014; Lundberg, 2011; Nelldal and Andersson, 2012). Fig. 1 shows rail travel's share as a function of travel time by rail in the combined rail and air market, based on data from Europe and Japan (Lundberg, 2011), with decreasing rail shares as travel time increases. Currently, virtually all trips under 2 h are made by rail and at 8 h, rail's share is down to some 15%. A modal shift could be achieved either by shortening travel times on specific routes (e.g. constructing new high-speed railways or improving connections at transits), by changes in preferences where people accept longer travel times, or through policy instruments stimulating avoidance of the shortest trips by air. If a new high-speed railway is built, a specific route could be expected to shift along the curve towards the upper left in Fig. 1. If people were to accept longer travel times, the same rail share could be achieved at longer travel times and the curve in Fig. 1 would shift to the right. The same rail share could then be reached at longer travel times and a higher rail share could be achieved for a specific route. For instance, if people accept + 1 h in train travel time, the curve shifts to the right and the rail share at 5 h train travel time would increase from about 35% to 47%. As possibilities to work or stream movies on-board trains improve, people might value travel time differently, making such a preference shift more likely (Lyons and Urry, 2005). Likewise, travel time for night trains may not be valued equally to day trains since some of the travel time is spent sleeping (Zhao et al., 2015), and this time could possibly be subtracted when applying the travel time/market share ratio. Here we assume that night trains have the same rail share as day trains at 6 h shorter travel time (c.f. Zhao et al., 2015), which means that at 12 h travel time night trains would reach the same market share as day trains at 6 h travel time. Policies steering towards avoidance of the shortest air trips can be seen e.g. in the COVID support granted to Air France KLM and in authorities' travel policies.

To assess the potential for modal shift, the long-distance travel of the Swedish population was analysed using the Swedish national travel survey from 2017 (SCB, 2018). The air travel of the Swedish population can be seen in Fig. 2, where air travel volumes (pkm) are distributed in intervals by (a) distance and (b) the corresponding travel time by rail if travel shifted from air to rail. As can be seen, over 60% of the air travel volume is not at all accessible by train.

The calculated potential for modal shift of different measures is shown in Table 2. With the same rail network and travel times as today, and assuming that people would accept + 1 h longer travel time by day train, then about 1.0% of air travel volumes (pkm) would shift to rail (2.5% of air volumes within Europe). At + 2 h this yields 2% of air travel volumes (5% within Europe).

With a substantial extension of the high-speed railway network in Europe, most of the continent can be reached from Sweden within 12–15 h instead of the current 20+ hours (Sterky et al., 2019), which could make travel possible during the day or overnight. Assuming faster trains, about 2.0% of the total air travel volumes would shift to rail (5.0% within Europe). Assuming increased preferences for night trains as described above, this would achieve a 1.7% shift of air travel volumes (4.3% in Europe). If all air trips under 500 km would shift to rail, this would represent 2.3% of the total air travel volume (5.7% within Europe).

Shifting air travel volumes to rail could also be realised through mixed modes, i.e. combinations of rail and air, which reduces the air travel distance with only moderate increases in travel time. This could be achieved either by travelling by air in one direction and by rail in the other, or by combining both modes in both directions. Travelling from Stockholm to London for instance, the climate impact could be reduced by approximately 30% by taking the train to Copenhagen and then flying to London. Depending on the origin and destination when flying, transits may already be needed at an airport with a larger route network, e.g. in Copenhagen. If new HSRs are built in Sweden, travelling from Stockholm to Copenhagen airport would take approximately three hours (Swedish Transport

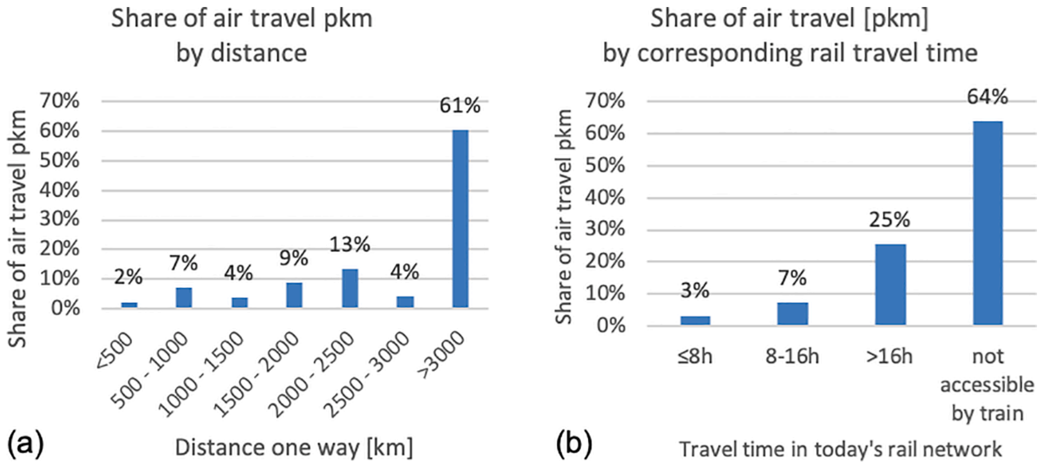

Fig. 2. Air travel volumes (pkm) of the Swedish population in 2017 distributed by (a) distance and (b) travel time by rail if air travel were shifted to rail, with today's rail network. Note that distances by rail are often longer than by air. Own calculation based on travel by Swedish residents (SCB, 2018) and Sterky et al. (2019).

Table 2
Potential for modal shift from air travel by different measures. Note that rows cannot be added as trips would be double counted. Own calculation based on SCB (2018), Sterky et al. (2019), Lundberg (2011), and Nelldal and Andersson (2012).

Modal shift measure	Modal shift share (of air travel pkm)
Acceptance + 1 h	1.0%
Acceptance + 2 h	2.0%
High-speed rail (HSR)	2.0%
Night trains	1.7%
All trips under 500 km	2.3%
Mixed modes: Train one way for all flights (for flights to Western/Southern Europe)	14%
Mixed modes: Train to Copenhagen (for flights to Western/Southern Europe and Africa)	8.7%
Acceptance + 1 h, HSR, night trains, and Mixed modes Copenhagen	11%

Administration, 2021). Assuming that all flights to Southern and Western Europe from Sweden are viable for mixed modes, travelling by rail one way would shift 14% of total air travel volumes to rail (assuming no shift through higher acceptance of travel time or expansion of rail networks). Shortening the air travel distance, by travelling to Malmö or Copenhagen by rail and continuing by air to the final destination, for the same flights and for flights to Africa, could shift approximately 8.7% of air travel volumes.

Combining all of these modal shift measures (with an acceptance of +1 h in travel time, expansion of high-speed railways, increased preference for night trains, and mixed modes to Copenhagen) could achieve a 11% shift in travel volumes from air to rail.

3.2. Reduced specific energy use through more efficient vehicles and increased occupancy

There is continuous improvement in the fuel efficiency of new aircraft. Recently, geared turbo-fans allowing a higher by-pass ratio have been introduced in commercial aircraft, for instance in the Airbus 320 Neo. Lighter materials like carbon fibre also contribute to efficiency improvements, as do aerodynamic refinements. When including the effect of increased occupancy, the specific emissions have decreased by on average 1.9% per year since 1990 (Larsson et al., 2018). There is still potential for improvement in the traditional aircraft configuration, but it will require rather intense efforts just to keep up the present pace of improvement in the coming decades. ICAO (2019a) has developed four scenarios leading up to 2050 with a range of annual specific fuel efficiency improvements from 0.57% to 1.5% for the global fleet. These improvements are the combined effect of changes in technology and operations. The two middle scenarios labelled “moderate” and “advanced” give, respectively, 0.96% and 1.16% improvement annually.

One potential technology path is the open rotor concept. It commonly features contra-rotating propellers and a service speed that is somewhat lower than for turbofan aircraft. Seitz (2011) estimated that an open rotor aircraft may consume 20% less fuel than a corresponding sized turbofan aircraft, albeit at a 10% lower speed. Recent developments with geared turbofans (e.g. Airbus 320 Neo) have decreased the advantage to around 15%. The technology needs some further development and there are concerns regarding increased noise. Nearly the same improvement could be accomplished by an optimised traditional turboprop configuration at speeds around 600 kph.

For passenger cars, the key technology trajectory is electrification. However, there is some uncertainty regarding penetration for long-distance car travel. In the scenarios, we have assumed that 95% of passenger car kilometres use electricity or other renewable fuels in 2060, which is broadly in line with the Sustainable Development Scenario developed by IEA (2020). Regarding trains, there is still potential to further reduce energy use by means of improved aerodynamic properties and regenerative braking for example. However, the main benefit gained from train travel stems from the shift to it from aircraft and car travel. Consequently, improved train technology has mainly been used to increase speed – and thus market share – rather than reducing specific energy use.

Increased occupancy is an obvious way to improve fuel efficiency measured as kWh/pkm. For aviation, however, occupancy already in 2018 reached the level of 82% (ICAO, 2019b), and the remaining potential is therefore limited due to booking convenience. Furthermore, airlines have different seat configurations for the same aircraft model, with a mix of area demanding premium seats and area efficient economy seats. Increasing passenger density on aircraft by increasing the share of economy seats, could further improve specific fuel consumption. A more dense seat configuration can have 10–15% lower fuel burn per seat-km than the average for that aircraft (Park and O’Kelly, 2014). For long-distance car travel in Sweden, the average occupancy is 1.7 persons per car (Trafikanalys, 2020b), and for long-distance passenger trains the occupancy is between 50% and 65% depending on type of train (Transportstyrelsen, 2019).

3.3. Low-carbon fuels

3.3.1. Biofuels for drop-in use

The resource base for aviation biofuels will be a limiting factor given that most sectors of society will demand substantial volumes of biofuels to replace fossil fuels. Furthermore, the future total potential supply of sustainable bioenergy is highly uncertain. The use of dedicated crops to produce transport fuel is controversial while there is more consent around using forestry and agricultural residues. Using dedicated crops may increase food prices, which is especially problematic in developing countries. Indirect land use changes may also reduce or even cancel out the climate benefits of using some specific biofuels (Ahlgren and Di Lucia, 2014).

IPCC (2018) has compiled 85 scenarios limiting global warming to 1.5 degrees. The median for bioenergy use in these scenarios is 42 PWh/year. In IEA’s (2020) Sustainable Development Scenario leading to 1.8 degrees warming with 67% probability bioenergy use is 27 PWh in 2040 and 34 PWh in 2070. According to Creutzig et al. (2015), the global gross bioenergy potential from residues, reduced demand for biomass for cooking and optimal forest harvesting amounts to between 28 and 44 PWh by 2050. Searle and Malins (2015) include some energy crops but nevertheless end up with a lower interval of 17–33 PWh for the same year. In this context it is important to consider the conversion efficiency from primary woody biomass to transport fuel, which at present is between 50 and 60% (Petersen et al., 2015).

What share of total bioenergy supply that may be used for aviation depends on several factors. An important factor is obviously the extent of electrification of road vehicles. If the Paris agreement is to be fulfilled, it is likely that a large share of passenger cars globally in 2060 will be electric-powered, although some biofuels may still be used for long-distance car travel. The potential for electric trucks is somewhat smaller but still high compared to aviation. For the distribution of goods in urban areas, battery-electric trucks may be used and for long-distance trucking, hydrogen fuel cells is considered a viable alternative in the long run.

Some recent results indicate that biofuels may somewhat reduce high-altitude effects in the form of contrails and cirrus clouds. The reason is that at least some biofuels emit lower quantities of particles and this means that water vapour has fewer condensation nuclei. (Kärcher, 2015; Zhang et al., 2016; Moore et al., 2017). If these findings are confirmed, this would be an argument for using biofuels in aviation.

The future cost of biofuel for aviation is complex to predict and will vary depending on the type of primary biomass. A rough estimate is that large-scale future biofuel production would result in a cost between EUR 80 and 200/MWh (European Commission, 2017a; European Commission, 2017b; de Jong, 2018). This may be compared to the price of fossil kerosene which was EUR 42/MWh in summer 2019 when the oil price was at 60 dollars per barrel (IATA, 2020a).

3.3.2. Electrofuels

A fuel alternative that has been increasingly discussed is electrofuels (also called power-to-liquids/gas/fuels or synthetic fuels), which are produced by mixing CO_2 and hydrogen in a reactor to form energy carriers such as methane or synthetic aviation fuel (kerosene). Aromatics in the fuel, the main source of particles, may largely be avoided in the process, which means that non-CO2 effects may be significantly reduced. The production of 10 kWh of electrofuel requires roughly 20 kWh of electricity, which indicates a modest energy efficiency (Brynolf et al, 2018). With the rapid increase in intermittent energy sources like wind and solar, the use of cheap "surplus" electricity has become an interesting option for the production of electrofuels and/or hydrogen. However, only using surplus electricity from intermittent peaks in electricity production would result in a low utilization of the electrolyser, which would then entail a substantial cost that would cancel out a part, or all, of the gain from cheaper electricity (Brynolf et al, 2018).

Brynolf et al. (2018) has conducted a review of production costs for electrofuels based on a large number of studies. They conclude that the cost of producing liquids (like kerosene) in 2030 will fall in the range EUR 110 to 340/MWh and give a base (mid) estimate of around EUR 170/MWh. The latter holds for an electricity price of EUR 50/MWh and a capacity factor for the electrolyser of 80%. The base estimate is nearly four times higher than the price of fossil kerosene in 2019 (IATA, 2020a).

Since hydrogen is used in the process, electrofuels will likely be more expensive than hydrogen and involve higher energy losses. On the other hand, electrofuels for aviation has the advantage of not requiring new aircraft and fuel distribution systems. For aviation purposes, electrofuels will be around 20% more expensive than hydrogen, when energy losses for liquefaction of the hydrogen is taken into account.

A restricting factor for electrofuels may be the supply of concentrated CO_2 from point sources (Reiter and Lindorfer, 2015), since CO_2 capture from the air is many times more expensive. It should also be noted that the more CO2 that is captured and stored underground (Carbon capture and storage (CCS) or Bioenergy carbon capture and storage (BECCS)), the less will be available for producing electrofuels. That is, the more demanding the overall climate target is, the less CO_2 from point sources might be available for producing electrofuels.

3.3.3. Hydrogen.

Switching to hydrogen would require completely new aircraft designs as well as production facilities and distribution networks for hydrogen. The emissions of water vapour increase by a factor 2.5 when hydrogen replaces kerosene, but emissions of particles are largely avoided. According to Ponater et al. (2006) the net effect is that radiative forcing from contrails is reduced by 16–28%. In order to get a higher reduction hydrogen aircraft would, at least occasionally, need to fly at lower altitudes, typically below 8–10,000 m. This would in turn slightly increase fuel consumption.

To accommodate a sufficient amount of energy in the aircraft, the hydrogen needs to be liquefied. This is an energy-intensive process. According to the US Department of Energy (2009), the minimum theoretical energy loss corresponds to 12% of the hydrogen energy content. Actual liquefaction requirements are higher, typically between 30 and 40%, while novel methods may come down to 21% (ibid).

For hydrogen to reduce the climate impact of aviation substantially, it needs to be produced with carbon–neutral energy sources like wind and solar. The cost of hydrogen produced by electrolysis from solar and wind generated electricity differs substantially between sources, mainly due to the electricity price and the utilization rate of electrolysers. A mid-range estimate by Brynolf et al. (2018) for hydrogen production in 2030 given an electricity price of EUR 50/MWh is EUR 110/MWh. Assuming that energy losses from liquefaction and "boil off" amounts t0 21% (US Department of Energy, 2009), this corresponds to a price of "fuel in aircraft" of EUR 140/MWh. This may be compared to the price of fossil kerosene which was EUR 42/MWh in summer 2019 when the oil price was at 60 US dollars per barrel (IATA, 2020a).

3.3.4. Electrification

Aircraft require fuel with a high energy content. Conventional jet fuel (A-1) has an energy content of 11,900 Wh/kg which may be compared to state-of-the-art car batteries which have an energy density of around 200 Wh/kg (measured at battery pack level). That is, jet fuel has a 70 times higher energy content. An electric propulsion system has a higher efficiency than a jet engine, but even taking that into consideration it still means that the effective energy content is more than 30 times higher for the conventional propulsion system. Furthermore, while a conventional aircraft gradually gets lighter during a flight, a battery-powered aircraft does not.

Schäfer et al. (2019) have shown that if the energy density of battery packs were to increase fourfold to reach 800 Wh/kg, then all-electric aircraft could be able to serve distances of up to 1100 km. If this whole segment were to become all electric, about 15% of all RPK (revenue passenger kilometres) could be carried out without any use of combustion engines (ibid). According to Schäfer et al. (2019) a battery energy density of 800 Wh/kg could be achieved at around mid-century, referring to an annual increase in specific energy of 4% since 2000, as concluded by Crabtree et al. (2015). The analogy with car batteries may be somewhat flawed, however. The extraordinary safety concern in aviation might render the development slower than in the car sector, since the risk of fire usually increases with the energy density of batteries.

An important factor to bear in mind is that the aviation sector suffers from substantial inertia. Historically, the time-span from the start of development of a new aircraft design until the entire fleet has been replaced has been between 45 and 65 years (IPCC, 1999), of which aircraft design and certification take 5–10 years, successful production runs 15–20 years, and aircraft lifespans are 25–35 years. Although radically new configurations like all-electric or hydrogen aircraft would tend to increase the time for aircraft design, the time for production runs and aircraft lifespans could likely be reduced, albeit at a cost, due to the urgency of mitigating climate change.

3.4. Improved organisation of air traffic

Tailored flight paths to avoid contrails and aircraft-induced cirrus cloud formation seem to have the potential to reduce the climate impact from aviation substantially. Although organisational inertia may be high at present, these kinds of measures are interesting since from a technical point of view they could be realized within a few years if sufficient political pressure were applied. There have been several studies on the potential of altering flight paths horizontally and/or vertically. The results of Sridhar, et al., (2010), covering the US airspace, indicate that a rerouting of flights theoretically could yield a 53% reduction in contrails at the expense of a 3% increased fuel consumption. Yin et al. (2018) have made a full-year simulation of potential contrail distance reduction for trans-Atlantic flights, but have not estimated the reduction of climate impact. They found that a 40% reduction in contrail distance can be achieved with an increase in flight time of less than 2%. A recent study covering the Japanese airspace reached the conclusion that diverting 1.7% of the flights could reduce climate impact by 60% (Teoh et al., 2020).

These studies have different geographical scope and used different methods which means that further research is required to get more robust results. In the scenarios for 2060, we have used two levels of reduction of non-CO_2 effects due to rerouting of flights, 50% and 80% (we also assume that biofuels can give an extra reduction in effects). These are net reductions, meaning that the increased CO_2 emissions from rerouting have been deducted from the gross reductions.

There is some potential in reducing fuel burn by shortening flight paths and the implementation of continuous descent in the approach to airports. While the theoretical potential of such measures is significant – IPCC (1999) has estimated it at 6–12% - practical progress has been limited in part due to administrative barriers. The Single European Sky initiative launched in 1999 aims to improve the performance of air traffic management. However, thus far the results have been modest. Between 2009 and 2016, the horizontal direct en-route extension (compared to minimum distance) decreased from 5.03% to 4.82% (European Parliament, 2020).

3.5. Limited long-distance travel

Long-distance travel can be limited by reducing the frequency of travel and/or the distance travelled, i.e. choosing destinations closer to home. Often, several destinations offer similar activities and experiences, such as visiting urban areas, providing a choice of destinations at different distances. There is no consensus on whether long distances to destinations has an attracting or deterring effect (Nicolau and Más, 2006) and in general, people have poor knowledge of the distances to different destinations (Riber Larsen and Guiver, 2013) as well as the order of magnitude of emissions from air travel (Wolrath Söderberg and Wormbs, 2019). Awareness of air travel's climate impact is increasing, however. When asked about their commitments for 2020 to mitigate climate change, 69% of respondents in the US and 75% in Europe claimed they will fly less (European Investment Bank, 2019). Furthermore, a recent study, based on changes in destinations and transport modes that people are ready to make, showed that emissions from Swedish residents' air travel could be reduced by 26% (Kamb et al., 2020). This suggests that people at least intend to reduce both the frequency and distances of their travel.

Business travel, which accounts for approximately 20% of emissions from Swedish residents' air travel (Kamb et al., 2018), is often less flexible regarding destination, with partners located at certain destinations. There are however options to reduce the frequency of travel by replacing face-to-face meetings with virtual meetings. Not all face-to-face meetings can be replaced without affecting the outcomes of the meeting, but virtual meetings tend to be more meaningful and fruitful when the participants have established relationships (Julsrud and Gjerdåker, 2013) and when less complex information is being exchanged (Roby, 2014). Nevertheless, virtual meetings have considerable potential to reduce business travel. For example, when virtual meetings were strategically implemented in a number of government agencies in Sweden, they showed a 10% reduction in CO_2 emissions per employee, compared to other government agencies that increased emissions per employee by 9% (Arnfalk et al., 2016). Similarly, the Swedish-Finnish company TeliaSonera halved the pkm per employee between 2001 and 2010 by revising their travel/meeting policy while at the same time providing excellent technologies for virtual meetings. Widespread experiences from virtual meetings during the Covid-19 pandemic are likely to further boost this development.

4. Scenarios for sustainable long-distance travel by Swedish residents 2060

The scenarios for future long-distance travel by Swedish residents outlined in this section all achieve the targets for 2040 and 2060 set-up in section 2. Obviously, they cannot materialise through efforts by Sweden alone, due to the international character of aviation. They require a more or less concerted development globally that leads towards the goals.

The five scenarios are:

1. Large scale drop-in fuel use.
2. High-speed rail.
3. Local, regional leisure travel.
4. Hydrogen aviation.
5. Multiple changes.

All scenarios involve fundamental changes to the socio-technical system of long-distance travel, although of rather different kinds. Change in travel preferences towards closer destinations is small in Scenarios 1 and 4, larger in Scenarios 2 and 5, and largest in Scenario 3. The public in general value the mitigation of climate change higher compared to the present in all scenarios. The most significant changes compared to the present are highlighted in the descriptions of the scenarios. It should be remembered, however, that many other changes are also necessary to reach the targets, although these are more or less the same for all the scenarios.

Business travel is reduced considerably mainly due to the extensive use of virtual meetings: by 60% in Scenarios 1 and 4, which are mainly technology/fuel driven; and by 80% in the other scenarios. The Covid-19 pandemic imposed an involuntary trial of virtual meetings and got many people used to working in this way.

All scenarios entail people accepting 1 h longer travel time by rail, except in Scenario 3 where 2 h longer travel time is accepted. In all the scenarios, 40% of viable trips (to Southern and Western Europe and Africa) also shift to mixed modes to shorten the distance travelled by air, except for Scenario 2 where the expansion of the high-speed rail network has enabled 80% of viable trips to shift to mixed modes. A continuation of the trend (prior to Covid-19 in 2020) of increasing rail travel has also been assumed, yielding, as a basis for additional changes specific to each scenario, a 30% increase in passenger-kms from 2017 up until 2060.

The fuel efficiency of aircraft is improved substantially in all the scenarios (see Table 3) and occupancy in air travel has increased to 85%. Two levels for drop-in fuels are used. In the Sustainable Development Scenario by IEA (2020), 2 PWh of biofuels and 2 PWh of electrofuels are used in aviation in 2060. To reflect the substantial uncertainty regarding the potential for drop-in fuels supply, we use a 25% higher level in scenario 1 and a 25% lower level in scenarios 2, 3 and 5. Deducting 10% for air freight, we then get 4.5 and 2.7 PWh, respectively. In Scenario 4, only half of the lower level is used (the biofuel) since electricity is used for producing hydrogen instead of electrofuel. Obviously, different combinations of biofuels and electrofuels could yield the same total amount of drop-in fuels. In Scenario 4, Hydrogen aviation, 5 PWh of electricity (10% more than is used to produce electrofuel in Scenario 1) is used to produce 2.85 PWh of hydrogen. That amount of electricity corresponds t0 about 8% of global electricity supply in IEA's Sustainable Development Scenario for 2060 or 19% of current global electricity supply. In all the scenarios, all-electric aircraft have captured 10% of the air travel market, except in Scenario 3, High speed rail, where it has captured 5%.

As pointed out in Section 3, the potential for reducing non-CO_2 climate impact by rerouting of flight paths is significant but uncertain. Two levels are therefore used in the scenarios, a 50% and an 80% net reduction, respectively. Both biofuels and electrofuels are assumed to give an extra 30% reduction in non- CO_2 climate impact on top of that achieved by rerouting of flight paths.

In all the scenarios, electricity or biofuels are used for 95% of long-distance car mileage in 2060 and fossil fuels used for the rest,

Table 3
Key characteristics of the scenarios for sustainable long-distance travel by Swedish residents 2060.

	2017	Scenario 1 Large scale drop-in fuel use	Scenario 2 High-speed rail	Scenario 3 Local, regional leisure travel	Scenario 4 Hydrogen aviation	Scenario 5 Multiple changes
Annual fuel efficiency improvement 2017–2060 (kWh/seat-km)	0.36 kWh/ pkm in 2017	1.1%	1.1%	1.1%	1.1%	1.4%
Slower aircraft, market share		20%	20%	20%	20%	50%
Reduced non– CO_2 impact due to rerouted flight paths (net effect)		50%	50%	50%	80%	80%
Global net aviation fuel use for passenger transport (including battery electric)	2.8 PWh	6.6 PWh	4.9 PWh	4.9 PWh	7.2 PWh	5.7 PWh
- Global drop-in fuel use for aviation, net	0 PWh	4.5 PWh	2.7 PWh	2.7 PWh	1.4 PWh	2.7 PWh
- Global fossil aviation fuel, net	2.8 PWh	1.7 PWh	2.0 PWh	2.0 PWh	2.6 PWh	2.7 PWh
- Hydrogen use, net	0	0	0	0	2.8 PWh	0

which is in line with the IEA (2020) Sustainable Development Scenario. ICE cars have a 30% lower specific energy use compared to 2017.

The key quantitative characteristics of the scenarios – based on Section 3 - are shown in Table 3 and 4.

In Fig. 3, the travel volumes in the scenarios are shown per mode for 2060.

Below is a description of the characteristic features of the five scenarios where the climate targets for long-distance travel are met. After each scenario, there is a section on the challenges specific to realising that scenario.

4.1. Scenario 1: Large scale drop-in fuel use

The main idea in this scenario is that emissions are reduced by technical measures, in particular by replacing fossil fuels with drop-in fuels on a large scale. Travel preferences are basically similar to 2017, but the concern for mitigating climate change has increased. Air travel now, in 2060, uses around 12% of total global gross bioenergy supply, or 3.8 PWh (net 2.25 PWh) since half of the drop-in fuel is produced from biomass. Total net aviation fuel use amounts to 6.6 PWh. As a comparison air travel in 2017 used 2.8 PWh fossil fuels. Between 2020 and 2030, the price of biofuel decreased due to improved fuel production technology. Later on this trend was reversed because of a growing competition for bioenergy resources. The rather high price of biofuels have contributed to reducing per capita air travel for Swedish residents by 44% compared to 2017. Given that Sweden's population has increased to 12 million people, this means that air travel by the total population decreased by 33%. Swedish residents' long-distance train travel has increased by 60%, mainly due to more travel in Sweden but also more travel to Denmark and Norway.

Challenges for realising Scenario 1: Large-scale drop-in fuel use

Conflicts over land use might be frequent in this scenario and there is a risk that biofuel production will compromise goals for biodiversity and coherent ecosystems. The high biofuel use may only be possible if the global population has converted to vegetarian diets to a large extent and road transport is mainly electrified. In particular the former will be challenging to realise. A possible way to avoid the competition for land could be to rely even more on electrofuels than the 50% of drop-in fuels. This would, however, increase ticket prices even more since electrofuels are predicted to be even more expensive than biofuels (see Section 3). The supply of CO_2 from point sources may also constrain the feasible volume of electrofuels. See a further discussion in Section 5.

4.2. Scenario 2: High-speed rail

The main idea in this scenario is that emissions are reduced by improving the alternatives to air travel, in particular high-speed rail. A high-speed rail network between the three major cities in Sweden was completed in the late 2030s (parts of this HSR network have formally been decided, but sufficient funding for the whole network was lacking and construction had not started as of July 2021, and thus the implementation of the project is still uncertain). In addition, the high-speed rail network in northern/central Europe has been much extended and the Fehmarn belt tunnel between Denmark and Germany has been completed. In 2060, rail has almost out-competed air travel in southern Sweden and to Denmark. When people travel by air, transfer is often done by rail in a way that minimises the leg by air. This means that for air trips to Southern and Western Europe as well as to Africa, the preferred airport is Malmö (Sturup) or Copenhagen (Kastrup). If travelling from Stockholm to London for instance, a 30% reduction in climate impact may be achieved by taking the train to Copenhagen and then flying to London. With a travel time of around 3 h from Stockholm to Copenhagen the increase in total travel time is around 1.5 h. In total, switching to rail by decreasing the length of the air leg has resulted in about a 7% reduction in air travel pkm in 2060 compared to the situation in 2017. Rail travel per capita has almost tripled compared to 2017. Rail has directly replaced more than 11% of air travel pkm, including decreased air legs. In addition, some air trips have been replaced by train trips to less remote destinations. Most travel companies offer trips combining different modes of transport, and travellers are guaranteed to get replacement trips if delays on one leg means that a connection is missed.

Challenges for realising Scenario 2: High-speed rail

A key barrier to realising this scenario is the high cost of building new high-speed rail lines. The planned high-speed rail lines

Table 4
Modal shift from air to rail in the scenarios for sustainable long-distance travel by Swedish residents 2060.

	Scenario 1 Large scale drop-in fuel use	Scenario 2 High-speed rail	Scenario 3 Local, regional leisure travel	Scenario 4 Hydrogen aviation	Scenario 5 Multiple changes
Modal shift	5.7%	11%	7.0%	5.7%	5.7%
Acceptance of longer travel times	+1h	+1h	+2h	+1h	+1h
Shorter travel time by extension of HSR	–	Yes	–	–	–
Mixed modes: Train to Copenhagen**	40%	80%	40%	40%	40%
Night trains* (travel time by rail)	8–12 h: 15% 12–16 h: 20% 16–24 h: 3%	8–12 h: 15% 12–16 h: 20% 16–24 h: 3%	8–12 h: 20% 12–16 h: 26% 16–24 h: 5%	8–12 h: 15% 12–16 h: 20% 16–24 h: 3%	8–12 h: 15% 12–16 h: 20% 16–24 h: 3%

* % out of pkm to Western/Southern Europe.

** % out of trips to Western/Southern Europe and Africa.

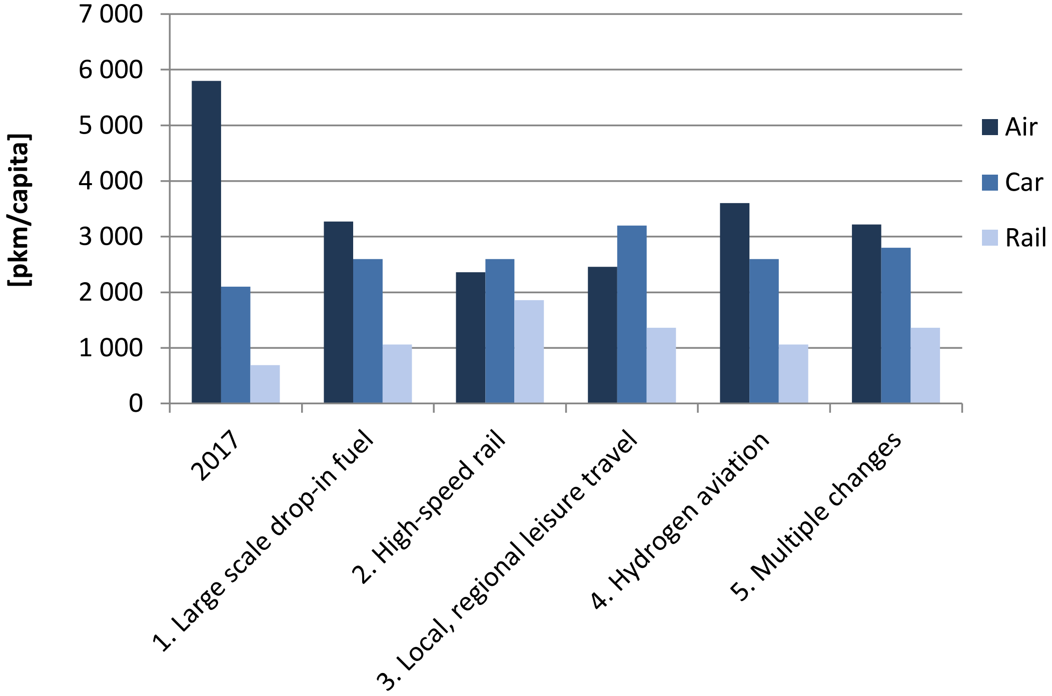

Fig. 3. Travel volumes in the scenarios for 2060, compared to 2017.

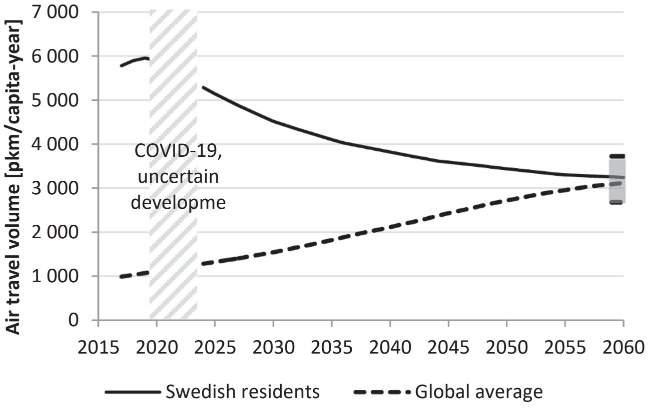

Fig. 4. Swedish and global per capita air travel in Scenario 5. The span in 2060 indicates resulting per capita air travel if the share for emissions from long-distance travel of total emissions varies between 10 and 17% (baseline is 13.6%). In 2020–2024 travel volumes can be expected to be strongly affected by Covid-19 (IATA, 2020b).

between Stockholm, Gothenburg and Malmo are estimated to cost around EUR 23 billion (SEK 230 billion). Another concern is the emissions of CO_2 associated with the construction of the tracks. The emissions for the construction phase are estimated at around 1.3 million tonnes of CO_2, assuming 80–90% reductions of emissions from cement and steel compared to 2015 levels (Trafikverket, 2021). Another challenge is that it typically takes at least 15–20 years to complete major HSR projects.

4.3. Scenario 3: Local, regional leisure travel

The main feature of this scenario is that people in general have adopted a less hectic lifestyle and that interest in spending vacations in Sweden and its neighbouring countries has increased. This transformation started in the 2020s and was triggered by three main drivers. The first was an increased interest in local and regional destinations partly triggered by the Covid-19 pandemic. This development was then strengthened by a greater focus on marketing local and regional tourist destinations that could conveniently be reached by train, bus or car. Secondly, concern about climate change contributed to changed travel habits. Finally, reduced working hours led to higher acceptance of longer travel times, which in turn increased the rail share. People in general accept 2 h' longer travel time when travelling by rail compared to 2017.

Rail travel in 2060 is now more than twice the volume it was in 2017, and long-distance car travel, in particular to holiday cottages, has increased by 50%. The stock of holiday cottages is used more intensively compared to the turn of the century, a change that have been enabled by a multitude of renting and exchange concepts, some similar to the Airbnb business model of 2020. Furthermore, even though the Paris targets of limiting global warming to two degrees have been reached, the temperature increase in Sweden has been higher, 3–5 degrees, leading to an extended summer season. Less hectic lifestyles have increased rail travel to northern Europe despite the planned high-speed rail lines in Sweden never being realised. Night trains depart from major Swedish cities in the evening and arrive at cities like Berlin, Basel, Brussels, Paris, and Amsterdam the next morning. Since people on average work fewer hours over the year, they can stay away for longer periods while going away less often. Air trips to other continents are on average made three to four times during one’s lifetime.

Challenges for realising Scenario 3: Local, regional leisure travel

This future requires a substantial change in preferences, diverting the focus away from distant and exotic tourist destinations. Given the climate and light conditions in wintertime in Northern Europe, this development would imply a disruptive shift. However, there are also some possible external factors or events that could push the development towards a future of this kind, like recurring pandemics similar to Covid-19.

4.4. Scenario 4: Hydrogen aviation

The main idea in this scenario, similar to Scenario 1, is that targets should be met primarily through technical solutions, but here hydrogen produced by renewable power is the preferred choice. At almost all airports globally, two kind of fuels are offered: Jet A-1 (mix of fossil and renewables), and liquid hydrogen. The first commercial hydrogen aircraft entered service in the mid-2030s. In 2060, the share of aviation by hydrogen-powered aircraft is increasing and is at present nearly 40%. The hydrogen aircraft adapt flight paths so that the increased emissions of water vapour should not induce contrails or contrail cirrus. This means that flight altitudes are sometimes below 8000 m. Hydrogen is produced by electrolysis using 5 PWh of electricity globally from solar and wind power. This may be compared to the total global electricity supply in 2017 which was at 27 PWh. Aircraft and fuel distribution are somewhat more expensive than was the case for kerosene-fuelled aircraft around 2020, but willingness to pay for sustainable long-distance travel is high. These preferences combined with a high concern for mitigating climate change made possible the historic international agreement in the 2020s to make a concerted switch globally towards hydrogen as the fuel for air transport. Air travel per Swedish resident is 38% lower than it was in 2017. Challenges for realising Scenario 4: Hydrogen aviation

This scenario entails the most radical transformation of aircraft configurations. Since the airline industry is, for good reasons, very concerned about safety and the development of radically new configurations is costly, a large impetus would be required. An agreement among key global actors (nations and the aviation industry) is a central part of this scenario and was necessary in order to assure aircraft manufacturers that their huge investments in designing new hydrogen aircraft would pay off. Given that aircraft and fuel will be more costly, a significant resistance may be encountered from countries that do not have climate change mitigation as a top priority (Dincer and Acar, 2016). Even if this major barrier could be overcome, it would take decades until the entire global fleet consisted of hydrogen aircraft. That is, if it is (optimistically) assumed that a global decision (formal or informal) is taken in the mid-2020s, kerosene aircraft will probably not have been phased out completely until around 2070 at the earliest. It may be possible to speed up this shift somewhat by prematurely scrapping aircraft, but this would obviously add even more costs to an already expensive aircraft configuration.

Furthermore, how to limit emissions until hydrogen aircraft are deployed on a significant scale is a major challenge. In this scenario drop-in fuel is used as an intermediate solution to reach the 2040 goal. Another option for containing emissions by 2040 may be to limit air travel volume via strong economic instruments. Since this scenario contains more or less unchanged preferences, it is doubtful that such a policy would be accepted.

4.5. Scenario 5: Multiple changes

In this scenario, reduced climate impact has not been achieved by any single radical transformation, but rather a number of incremental ways of reducing emissions have been used to the highest extent possible. Biofuels and electrofuels have been promoted and constitute 45% of air pkm travelled. Air traffic routes are organised to produce as little warming from contrails and contrail cirrus clouds as possible. Leisure travel by air in 2060 is 36% lower per capita than in 2017, while business travel is down by 80% due to the increased use of virtual meetings. Denser seating layouts on all aircraft has increased and reduced specific fuel consumption by 4%.

The least conventional feature of this scenario is that open rotor (or advanced turboprop) aircraft which are some 15–20% slower than turbofan aircraft have taken large market shares. This has reduced energy use per passenger-km by an additional 10–15%. Furthermore, they fly at altitudes below 8000 m, which means that they generate virtually no climate impact due to contrails and aircraft-induced cirrus clouds. These aircraft are used for a large share of flights up to 3000 km. For a trip from Stockholm to London, the travel time with these aircraft is about half an hour longer than with a conventional turbojet aircraft.

For 40% of trips to Southern and Western Europe, rail is used to get to Malmö or Copenhagen from where the trips continue by air. This practice has reduced air travel by around 4% and it started already in the 2020s. When domestic air travel declined, the regional turboprop aircraft were increasingly used in combination with rail for trips to Central and Western Europe. Swedish residents spend their vacations in Sweden and adjacent countries to a high extent, although not to the same extent as in Scenario 3. Rail travel has more than doubled, and car travel is up by one third, partly due to an intensified use of leisure houses within Sweden.

Challenges for realising Scenario 5: Multiple changes

This scenario is quite feasible from a technological point of view. One barrier, however, is that aircraft manufacturers and airlines must develop and use turboprop/open rotor aircraft despite being 15–20% slower than conventional aircraft and less comfortable due to more turbulence at lower flight altitudes. A concerted technology procurement led by the EU might be a way of overcoming this barrier. Although there are no disruptive transformations required in this scenario, the sheer number of changes, many of which need to be agreed on in international fora, will demand a highly competent and committed political system.

5. Discussion

One aim of using target-fulfilling scenarios is to identify strategic choices. Since developments external to the long-distance travel sector may evolve in various ways, it is preferable to identify flexible and/or robust strategies. A related question is which scenarios require early decisions to trigger a radical transformation of the long-distance travel sector. Due to the great inertia of aircraft development and fleet turnover, it is clear that Scenario 4 *Hydrogen aviation* requires a rather early decision in order to reach the 2060 targets. It is also necessary that a sufficient share of key global actors agree on such a decision in order to assure aircraft manufacturers and other actors that hydrogen will be the fuel of the future. Scenario 2, High speed rail, although to a lesser extent, has a similar challenge since it takes typically at least 15–20 years to complete major HSR investments.

Scenarios 1, 3 and 5 seem to have better chances of achieving the mid-term target for 2040, that is, 575 kg of CO_2-eq. per capita. However, the high level of biofuels in Scenario 1 poses challenges to realising this scenario. The amount used by aviation depends on the total bioenergy availability as well as the share used by aviation, both of which are rather uncertain factors. The future average diet and in particular the level of meat consumption, and the degree of electrification of other transport modes, are two key factors. Synthetic aviation fuel could theoretically compensate for a lower supply of biofuels, but then other challenges come into play. High cost (see Section 3.3) could increase the total ticket price by some 40–50% by 2040. IEA (2020) only assumes a small share for synthetic fuel by 2040 in their Sustainable Development Scenario. Competition with carbon capture and storage (CCS/BECCS) for concentrated streams of CO_2 may also limit the use of electrofuels.

A key assumption behind the scenarios is that Swedish residents' air travel would be close to the global average in 2060, in contrast to the current situation where it is nearly six times higher (Kamb et al., 2018). In Fig. 4, the development for average Swedish resident and global per capita air travel up to 2060 is schematically shown for Scenario 5. It means that Swedish residents' air travel per capita would decrease by 44% while in the same period global average air travel per capita would increase by around 216%. This global level could be compared to the study by Sharmina et al. (2020), in which an increase of air travel per capita by around 85% until 2050 is judged as consistent with limiting global warming to 2 degrees. In Airbus (2019) market forecast, made prior to Covid-19, global air travel demand was projected to increase by 4.3% annually between 2019 and 2038. In our Scenario 5 the average increase in global air travel between 2017 and 2060 is 2.7% annually.

It could be argued that developing countries would not be able to increase their air travel to this extent, since their income levels may not develop sufficiently fast to afford it. But, on the other hand, there are distributional arguments for each global citizen having an equal "carbon budget" at their disposal to use for all their future emissions. Furthermore, it is noteworthy that in all scenarios, the share of total global primary energy supply that is used by passenger aviation in 2060 is significantly higher than in 2017.

The emissions from long-distance travel as share of total emissions is obviously a critical factor when assessing allowed volume of air travel. Fig. 4 shows the levels of global air travel in 2060 that would be consistent with a share for long-distance travel of total GHG emissions of between 10% and 17%, the baseline assumption being 13.6%.

A challenge in Scenarios 3 and 5 is to accommodate more than a doubling of long-distance rail travel while no HSR tracks having been built between the three major Swedish cities. There are two main ways to realise this increase. Firstly, the occupancy on trains could be increased somewhat from the current (2017) level of between 50 and 65% (Swedish Transport Agency, 2019). Secondly, capacity could be increased considerably by longer trains and/or double-deck trains. It may be necessary to increase the platform length at some stations, but these are comparatively small investments.

A better understanding of the conditions for the formation of contrails and cirrus clouds may have implications for the choice of fuel, since there is some evidence that certain biofuels for aviation may reduce emissions of particles and consequently probably also contrail formation (Kärcher, 2015; Zhang et al, 2016; Moore et al, 2017). It should be noted, however, that the same effect may be achieved by modifying fossil jet fuel, albeit with somewhat higher energy losses and costs. Zhang et al (2020) has pointed out key research areas with regard to the climate impact of aviation biofuels. In addition to further research about the chemical properties and atmospheric reactions of different biofuels they highlight the need to investigate in what climate zones it may be most beneficial to use the limited supply of biofuels. Here it should be noted that if aviation in the longer term after 2060 should have truly net zero greenhouse gas emissions, paying for carbon removal such as bioenergy with carbon capture and storage (BECCS) in other sectors might be needed to compensate for some unavoidable remaining non-CO2 climate impact.

An important assumption in all scenarios is that they only consider measures within the sector of long-distance travel itself. We believe that this is a sound principle in general. In a world heading towards zero carbon emissions, there would be limited room for offsetting emissions in one sector by reducing emissions in another sector. However, if for instance the aviation sector were to achieve negative emissions in another sector, which are truly additional, then that could provide an alternative path for the next decades. Consider the option of rather expensive electrofuels. This option would imply production of fuel from electricity and captured biogenic carbon that would replace fossil jet fuel in aircraft. From an energy systems perspective, a path with equivalent effect would be the BECCS solution where the same stream of biogenic carbon would instead be stored, for example in aquifers, enabling continued use of fossil fuels in the aircraft but with the same net GHG emissions as in the electrofuels case. Such a solution could indeed prove to be more cost-effective. Estimates regarding CCS/BECCS point towards costs of 100–200 Euro per ton of CO_2 (IPCC, 2018). Assuming such a cost and an oil price at 80 dollar per barrel, fossil air fuel combined with payment for BECCS would yield roughly half the cost compared to using electrofuels given an electricity price of EUR 50/MWh (Brynolf et al., 2018). Achieving the 1.5 degree target, however, would most likely require net negative emissions in the second half of this century IPCC (2018), and for this to happen, concentrated streams of biogenic carbon would be needed to achieve a net reduction in carbon in the atmosphere, rather than for offsetting a continuation of fossil fuel emissions in other sectors. Thus, the level of ambition regarding mitigating climate change will significantly impact the choice of fuel for aviation.

6. Conclusions

A general conclusion is that there is no silver bullet that could make long-distance travel in line with the Paris agreement. All the scenarios explored in this paper are associated with considerable challenges, albeit of different character.

A key conclusion from this paper is that all scenarios require a significant reduction in air travel volumes per capita for Sweden and similar countries. The reduction of air travel per capita in the scenarios are between 38 and 59%. At present (early 2021), the Covid-19 pandemic has almost halted global air travel. Historically, crises like 9/11 2001 have had a rather short-term impact on air travel, but it remains to be seen if that will hold for the Covid-19 pandemic as well. In any case, it is important to prepare limiting policies for a case where air travel tend to retain pre-Covid growth rates. Even though temporary financial support for airlines to survive may be necessary, it should be kept in mind that to a large extent aviation is exempt from climate taxation and value added tax, and that remediation of this is required in due time. Another conclusion is that there will likely be no need for increased airport capacity in Sweden or similar countries, assuming that the Paris targets should be met.

We have found that the effect of a direct replacement of whole air trips by building a high-speed rail network in Sweden and the rest of Northern Europe (Scenario 2) is modest. However, the effect may be higher if travellers are willing to combine rail and air for a certain trip and if they are willing to change to closer destinations which may be feasible to reach by rail, as in Scenario 3. A substantial improvement in railway services may also increase public acceptance for increased taxes on aviation, although the lead times for construction postpone this effect.

Regarding the fuel choice for aviation, there are three main candidates: drop-in biofuels, drop-in electrofuels, and hydrogen. Battery-powered electric aircraft is a niche technology in all scenarios for the shortest distances. Drop-in fuels have the advantage of not requiring new aircraft and fuel distribution systems. This shortens the lead time for their implementation considerably. On the other hand, biofuels are constrained by a limited supply and electrofuels are electricity-intensive, will be rather expensive, and require concentrated streams of CO_2 which may be needed to achieve negative emissions. Hydrogen may be produced from solar or wind at a price somewhat lower than the price of electrofuels, and is not restricted by competition for concentrated streams of CO_2. However, this path requires a full renewal of the global aircraft fleet, which will take several decades, even if incentives for premature scrapping of aircraft are introduced. Some biofuel use, at least in the period up until 2040, is a common feature of all the scenarios outlined in this paper. However, a decision must be made rather soon as to what will come, be it more biofuels, a combination with electrofuels, or a shift to hydrogen.

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CRediT authorship contribution statement

Jonas Åkerman: Conceptualization, Methodology, Writing - original draft, Supervision, Project administration, Funding acquisition. **Anneli Kamb:** Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft. **Jörgen Larsson:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Jonas Nässén:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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