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Carbon footprint effects of shifting from flights to night trains for Swedish tourism

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ABSTRACT

Changes in travel behaviour are needed to tackle the climate impact associated with long-distance flights, including a switch to sustainable transport modes. In this paper, we analyse scenarios of carbon footprint reduction associated with a switch from flights to night trains for holidays in Europe for the case of Sweden, including outbound, inbound and domestic tourism. We use a prospective lifecycle assessment framework combined with results from a stated preference experiment to determine the impact of future mode shift behaviours. Our results indicate that a mode shift could be triggered by progressive night train policies resulting in (i) fewer transfers and (ii) price levels similar to those of flights. The shifts from flights to night trains could result in 9% lower cumulative carbon footprint in relation to a baseline travel demand scenario for the period 2025–2050. Decarbonization of long-distance travel in line with the Paris Agreement would likely require a combination of many different types of measures including a shift to low-carbon fuels.

1. Introduction

Tourism is a carbon-intensive activity; air travel alone contributes to 3.5% of the anthropogenic global climate impact (Lee et al., 2021). Despite the disruption of this trend due to the COVID-19 pandemic, with a tourism demand in Europe of only 30% compared to pre-pandemic levels (UNWTO, 2021), the airline trade association IATA estimates that air traffic in Western Europe will reach 2019 levels no later than 2024, followed by a continuous increase (IATA, 2022a). In 2022, European air passenger traffic reached 78% of 2019 levels (IATA, 2022b), which is in line with the estimated full recovery by 2024. The goals of the Paris Agreement, however, imply a need to drastically reduce greenhouse gas emissions. The carbon footprint related to air travel can be reduced by adopting technological improvements in aviation, or by changes in travel behaviour, such as switching to closer destinations or greener transport modes instead of air travel (Kamb et al., 2020; Peeters et al., 2006).

Recent attention has been given to the potential of shifting travel demand to trains, either through high-speed or night trains, to reduce the carbon footprint of long-distance travel (European Environment Agency, 2020). In France, high-speed railways started in 1981and has increased steadily in recent decades, mainly for the purpose of domestic travel (European Court of Auditors, 2018; Nunno, 2018). Generally in Europe, international train travel suffers from limitations due to the heterogeneity of railway systems across countries, high personnel cost, lack of web-based platforms for cross-company ticket purchases, and the absence of arrival guarantees for travellers (Lena Donat et al., 2021). High-speed trains can compete with flights on trip distances of up to 800 kilometres (km) (Yin et al., 2015), but the potential use of high-speed trains is limited when it comes to longer trips. Night trains could play a relevant role for such longer trips. However, the potential of shifting longer trips from flights to night trains has been questioned since night train services have had difficulties to grow beyond niche markets and many night train connections have been closed in recent decades (Gleave et al., 2016).

The year 2021 was named the European Year of Rail by the European Commission and is expected to boost train adoption in Europe, including a night train renaissance. An action plan was developed aiming to make cross-border train services more affordable, which includes making the ticketing system more customer-friendly and helping operators to upgrade their rolling stock (European Commission, 2021a, 2021b). New train companies like European Sleeper and Midnight Trains are also

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entering the market, offering services from 2022 onwards (Burroughs, 2021; Potter, 2021). Larger companies, such as the Austrian ÖBB, are expanding their fleets and offering new direct train connections that will link major European cities (ÖBB Nightjet, 2022). Moreover, several European countries indirectly support the competitiveness of trains by means of air passenger taxes, while France has even introduced a short-haul flight travel ban for destinations reachable by train in less than 2.5 hours (h) (Ledsom, 2020).

The role of night trains will be essential for European destinations that cannot be reached in a reasonable time by day train, such as those on the Iberian Peninsula and in Scandinavia. As for the latter, a new tunnel, the Fehmarn Belt Fixed Link (referred to as the Fehmarn Belt tunnel), is currently under construction between Germany and Denmark to reduce travel time between the Scandinavian countries and central/southern Europe (Ramboll Group, 2022). Future technological developments in aviation and railway systems, as well as related energy systems, will also influence the future carbon footprints of long-distance travel (Åkerman et al., 2021; Larsson et al., 2022). The potential of night trains to make long-distance travel more sustainable in Europe has been highlighted (Lena Donat et al., 2021), and the impact on carbon dioxide emissions due to air travel demand reductions related to high-speed railway adoption has been estimated for China (Strauss et al., 2021). A scenario analysis of how reduced travel time and reduced ticket prices influence modal shifts and travel-related CO_2 emissions in Germany shows that trains will become a more important mode in the future (Nordenholz et al., 2017). Further, the Dutch (Heufke Kantelaar et al., 2022) and Swedish (Curtale et al., 2023) willingness to consider night trains as alternatives to air travel have been estimated using stated preference experiments. Nevertheless, no academic research has been produced that quantifies the potential adoption of night trains to replace air travel, and its environmental benefits in the context of energy systems that decarbonize over time, to the best of our knowledge. The Swedish case is especially interesting given that (i) Swedish tourism will benefit from the Fehmarn Belt tunnel, and (ii) the strong social push towards train adoption from the movements "flygskam" (i.e., flight shaming) (Morrison, 2020) and "staying on the ground" (Ullström et al., 2021).

In this article, we aim to bridge this gap by assessing the effect on carbon footprints by replacing flights with night trains for Swedish tourism, including international inbound and outbound trips as well as domestic travel. We explore travel demand scenarios for changes in mode characteristics based on the stated preferences experiment performed by Curtale et al. (2023). The associated carbon footprint is estimated in the context of energy and transport systems in transition by applying a prospective lifecycle assessment framework that considers a pathway in line with current policies and trends, and a pathway in line with the Paris Agreement's goals. The article contributes with new insights into the emissions abatement potential of a mode shift for long-distance travel and the results are potentially of interest to policymakers, train operators and organizations in the transportation field.

The article is structured as follows. Section 2 defines the research method. Section 3 presents the results related to future travel demand and the associated carbon footprint. Section 4 provides a discussion of the results and policy implications as well as suggestions for future research. Finally, Section 5 highlights the conclusions.

2. Research method

This study uses scenario analysis to estimate the effects on the carbon footprint of different measures to promote night trains for long-distance travel. The scenarios also capture the influence of future decarbonization of long-distance travel, such as low-carbon aviation fuels and changes in Nordic and continental electricity systems. While this study only considers climate change impacts, we note that changes in the energy systems may adversely affect other sustainable development goals.

The functional unit of this study is long-distance travel for Swedish tourism, which is defined as trips within Sweden or between Sweden and other European countries that can be conducted through train connections longer than 6 h. Business travel is considered outside the scope of this study since it only accounts for about 20% of the carbon footprint of the Swedish population's air travel (Kamb and Larsson, 2019), and is governed by other factors than travel choices for leisure (e.g., value of travel time).

Results, in terms of travel demand, share of travel mode, and carbon footprints, are presented in aggregate for Swedish tourism over the period 2019–2050. To illustrate the impact of the scenarios on travel demand and carbon footprints, we highlight four cases for tourism between Stockholm (Sweden) and London (UK), Barcelona (Spain), Berlin (Germany) and Luleå (northern Sweden). The international destinations illustrate the impact for frequently visited destinations at different distances where night trains might replace flights. Meanwhile, the fourth destination illustrates the impact for domestic travel to a city in the far north of Sweden that is connected by night trains as of 2022.

The carbon footprint is estimated in carbon dioxide equivalents over a 100-year time horizon (GWP-100), including emissions of greenhouse gases as well as the non-CO_2 radiative forcing from combustion at high altitudes (see details in Appendix A.2 – A.4). The carbon footprint is calculated for scenarios of travel demand that depend on transport mode shifts, demand trends and increasing population. The mode shifts are estimated through a discrete choice model (Train, 2009) based on the results of the stated preference experiment by Curtale et al. (2023), measuring the impact of changes in mode characteristics on travellers' mode choices. The carbon footprints associated with passenger travel are estimated using an attributional prospective lifecycle assessment framework (Arvidsson et al., 2018) that considers future pathways for the choice of transport mode, which is considered the foreground system of the framework, as well as for background systems (including technological developments and the decarbonization of electricity generation, fuel production and battery manufacturing, as described in the carbon footprint layer, see Section 2.3). The resulting model can be conceptualized as composed of two layers: a travel demand layer, and a carbon footprint layer, as shown in Fig. 1.

A prospective lifecycle assessment can be either consequential or attributional (Arvidsson et al., 2018), where an attributional prospective lifecycle assessment provides a snapshot of the future given the evolution of foreground as well as background systems in line with scenario assumptions. A typical consequential prospective lifecycle assessment would have the intention to go one step further in order to evaluate what impact a specific decision, in our case increased use of night trains, would have on each sub-system (Jones et al., 2017), e.g., electricity generation. The latter is considered beyond the scope of this study.

2.1. Scenarios

The scenarios consider different ticket prices and numbers of transfers. Two levels (reference and altered) have been constructed, resulting in four different combinations affecting travel demand. The levels were inspired by Nordenholz et al. (2017), who estimated the potential for modal shifts to railways in Germany through scenarios based on travel time and travel cost. These four combinations are analysed in two different decarbonization pathways, resulting in eight scenarios in total (Table 1).

Ticket price. In the reference level, the price difference between the modes remains constant over the analysed period, with night trains being 30% more expensive than flights, based on estimations of the current average price difference (data and methodology are available in Appendix A.1). In the altered level, we assume a similar price for both alternatives as a result of a combination of higher energy costs (e.g., for increased use of low-carbon jet fuels) and/or taxation (e.g., air travel passenger tax or carbon tax).

Number of transfers. At the reference level, there are direct trains from

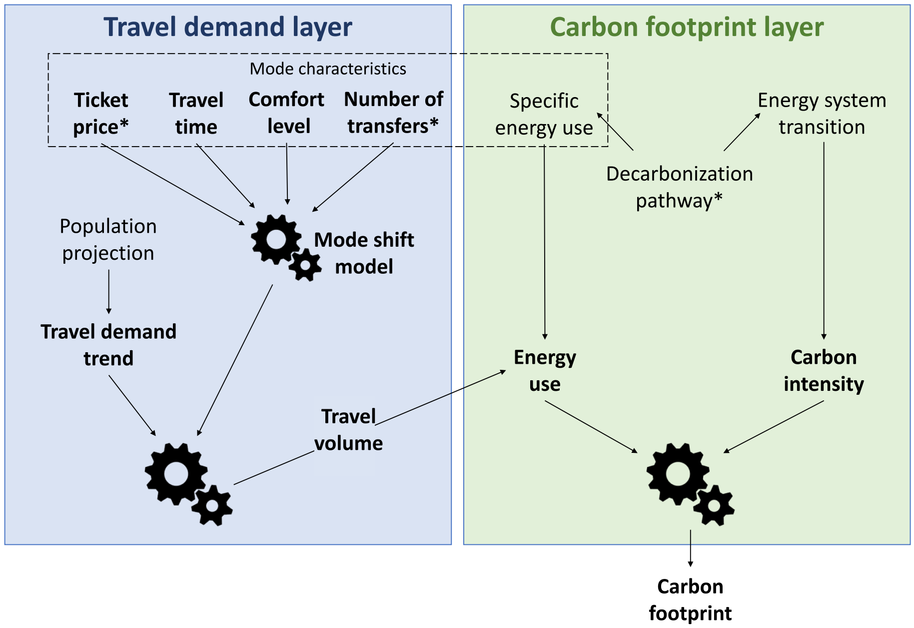

Fig. 1. Conceptual model. Note: Bold indicates estimated values, * = variables used in the scenarios.

Table 1
Levels of ticket price, numbers of transfers and decarbonization.

Variable	Reference level	Altered level
Ticket Price	*Current prices.* Travel by night train is 30% more expensive than flights.	*Similar price for night trains and flights.* Night train and flight have similar prices.
Number of transfers	*Current number of transfers.* The train connections will remain the same.	*Fewer train transfers.* New direct connections are proposed between major cities.
Decarbonization pathway	*Current technology trends.* Carbon footprints are based on current policies and expected technology development.	*Low-carbon technologies.* Carbon footprints are based on a pathway in line with the Paris Agreement's goals and associated technology development.

Malmö and Stockholm to Copenhagen, Hamburg and Berlin (Swedish Transport Administration, 2020). Additional transfers are required from other origins and to other destinations. In the altered level, we assume that major cities at medium distances (i.e., within 800 km) are directly accessible from Stockholm, Gothenburg and Malmö. One additional transfer is required from other origins, to smaller destinations at medium distances, to main cities at long distances, and to smaller destinations at long distances.

Decarbonization pathway. The two pathways considered are based on two scenarios by the International Energy Agency (IEA, 2020): *Stated Policies* and *Sustainable Development*. The former does not assume additional policy decisions for mitigating climate change and follows current trends (i.e., assuming that policies in their current form are fulfilled, such as the EU ETS reaching zero emissions by 2058 - in line with decisions made up until 2022), while the latter aims to hold the global mean temperature increase to below 1.8 °C, which is in line with the Paris Agreement's goals.

2.2. Travel demand layer

In the travel demand layer, we estimate origin-destination specific travel volumes for train and air travel in the base year (2019) and for the analysis period 2025–2050 (see Section 2.2.1). We excluded the 2020–2024 period due to post-pandemic uncertainty. The specific travel volumes are estimated by considering the travel demand trend in response to population projections, and the mode shift model that predicts the probability of shifting from planes to trains (see Section 2.2.2).

2.2.1. Travel demand trend

The travel demand trend, considered in terms of passenger-km (hereafter pkm), is specific for origin, destination, year and transport mode. Travel demand has been estimated based on two data sources: (i) the Swedish national travel survey carried out in 2011–2016 for domestic and outbound tourism, covering Swedish residents' travel behaviours (Transport Analysis, 2017) and comprising almost 50,000 respondents with a response rate of 31–42% depending on the year; and (ii) the Swedish survey on incoming tourists, carried out in March 2019 to March 2020, comprising 5,575 foreign tourists (Swedish Agency for Economic and Regional Growth, 2020). The data refer to 21 origin counties in Sweden (corresponding to NUTS 3), and 274 domestic and international destinations across European countries (corresponding to NUTS 3 for domestic destinations, and NUTS 2 for international destinations). Destinations that are not reachable by train and those more easily accessible by ferry compared to trains have been excluded from the analysis (Fig. 2). We considered data for leisure trips that included at least two nights away from home. The travel demand for flights from Sweden to destinations included in the analysis corresponds to 55% of the total travel demand for flights from Sweden to Europe (in pkm). The remaining 45% consists of business travel and the remaining leisure travel, which includes shorter trips in the time of stay, shorter trips in distance, and/or to destinations that are not easily reachable by train.

We considered inbound tourism from the rest of Europe to Sweden, outbound tourism from Sweden to the rest of Europe, and domestic tourism in Sweden. For outbound and domestic tourism, starting from the origin-destination-mode-year specific travel demand, we estimated future travel volumes based on travel demand trends and population projections provided by Statistics Sweden (2022). For inbound tourism, the only available information on the origin of the trip is the traveller's country of residence (i.e., NUTS 0). We adopted the following procedure to obtain the disaggregated inbound travel demand at NUTS 2 level. A ratio, α, between inbound and outbound tourism is calculated for each origin-destination pair with destination at NUTS 0 level, j, and origin at NUTS 3 level, i (eq. (1)).

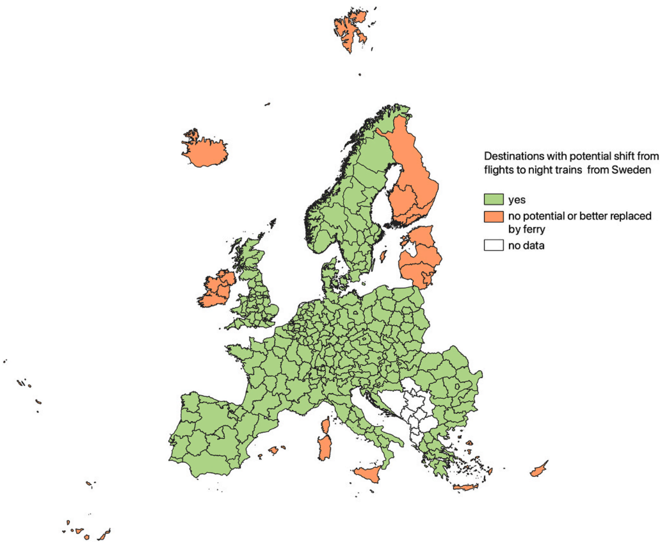

Fig. 2. Destination from Sweden with potential for a shift from flights to night trains. (Note: some small islands are displayed in green due to being part of an inland NUTS 2 region). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$\alpha_{ij} = \frac{Inbound_{ij_{NUTS0}}}{Outbound_{ij_{NUTS0}}} \quad (1)$$

To estimate the origin for inbound tourism at NUTS 2 level, we multiplied[1] the outbound origin-destination specific travel demand at NUTS 2 level with the ratio (eq. (2)).

$$Inbound_{ij_{NUTS2}} = Outbound_{ij_{NUTS2}} \bullet \alpha_{ij} \quad (2)$$

The average annual increase in air travel demand before the pandemic (1990–2017) was 2.9% per person (Kamb and Larsson, 2019; Larsson et al., 2018). The estimated year for returning to pre-pandemic levels of air travel is uncertain and estimated to be between 2024 and 2038 by different organizations (Swedish Government, 2021a). Given the vague reasoning behind a slow recovery, we assumed a recovery to the pre-pandemic growth trend from 2025 and onwards, in line with Larsson et al. (2022). The specific travel demand, for each origin and year from 2025 onwards, is adjusted by origin-specific population projections for future years, provided by Statistics Sweden (2022). The mode shift from plane to night train is estimated for future travel demand across origin-destination pairs and has been adjusted for origin-specific population growth.

2.2.2. Mode shift model

The specific mode shift for an origin-destination pair in a specific year was estimated by multiplying the average individual probability of replacing flights by night train journeys with the origin-destination-year specific travel volume by flight. The probability is based on the results of a stated preference experiment conducted on current air travel passengers in the Swedish population (Curtale et al., 2023). The experiment was conducted between March and April 2021 by Curtale et al. (2023) and included 1,711 surveyed participants, which is a representative sample of Swedish residents[2], to investigate their travel preferences for holidays at different European destinations. Respondents received a questionnaire including 4 to 8 choice tasks[3], depending on their travel habits. Each choice task consisted of two alternatives (flight and night train), characterized by four attributes (comfort level, number of transfers, total travel time, and price). Each attribute presented different levels in each choice task. This was done to estimate the respondents' sensitivity to travel-related attributes, in accordance with the choice modelling technique (Train, 2009). An example of a choice task is depicted in Fig. 3.

The impact of travel-related attributes on the probability of switching from flights to night train journeys was estimated through an error component model (Train, 2009) that was trained on valid answers from 1,571 respondents. A simulated maximum likelihood estimation method was applied with 500 Modified Latin Hypercube Sampling draws (Train, 2009; Walker, 2001) through the Apollo package in R (Hess and Palma, 2019). Based on future comfort levels, travel time, number of transfers, and travel cost, the resulting parameters from the error component model were used to estimate the probability of switching from flights to night train journeys for each origin-destination-year specific pair. The results of the error component model, reported in Table A.1, are discussed in detail by Curtale et al. (2023). The values of travel time, the number of transfers, ticket prices, and comfort levels imputed to the model were estimated as explained in Appendix A.1.

2.3. Carbon footprint layer

In the carbon footprint layer, we estimate the carbon footprint associated with the travel volumes obtained in the travel demand layer. The final output depends on the assumptions made for estimating carbon footprints of travel by plane or train, and their related supply chains. The carbon footprints represent estimates of the lifecycle climate impact of the respective modes of transportation, including emissions from the combustion of fuels, fuel production and electricity generation, battery manufacturing for electric planes (see Appendix A.3), and the additional climate impact due to non-CO_2 radiative forcing from combustion at high altitudes (see Appendix A.4). Assumptions are outlined for the two

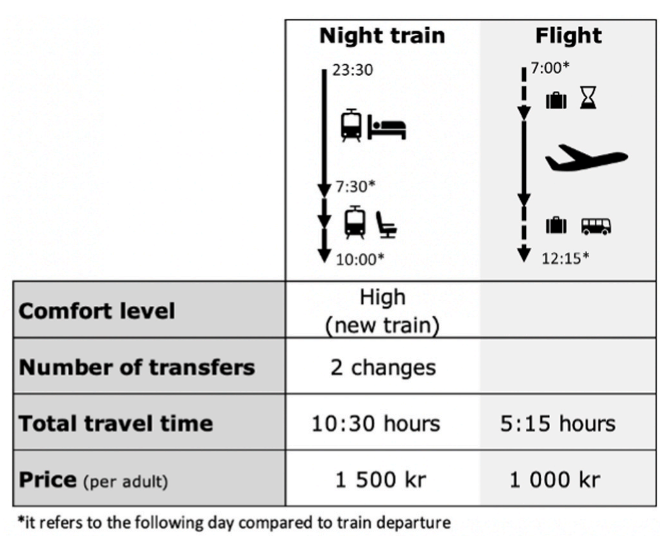

Fig. 3. Example of a choice task card used in the stated preference experiment (translated version). Tasks have been used to estimate the probability of switching from flights to night train trips, depending on the mode characteristics.

[1] Example: for 1 million pkm outbound tourists from Sweden to Germany and 3 million inbound tourists, the coefficient for Germany is 3. Therefore, if travel demand from Stockholm to Berlin corresponds to 200,000 pkm, we assume 600,000 pkm from Berlin to Stockholm (200,000 • 3).

[2] Data was collected in collaboration with Norstat market research agency (https://www.norstatpanel.com/sv).

[3] A task corresponds to a question where respondents had to select their favorite travel option from a set of alternatives.

decarbonization pathways: the *current technology trends* and *low-carbon technologies*.

The *low-carbon technologies* pathway in our analysis includes increasing market share for electric planes (reaching 30% of travel demand in 2050), increased use of alternative jet fuels (100% by 2045 for fuelling in Sweden and 63% by 2050 for fuelling in the rest of the EU) and a reduction in non-CO_2 radiative forcing by changing flight routes and reducing aromatics in aviation fuels (reduction of 60% by 2050). At the time of writing, these changes aligned with the European Commission's implementation plan for the European Green Deal (European Commission, 2022) and the European Commission's proposal for an emission reduction quota regulation for aviation (European Commission, 2021c).[4] The reasoning behind these technological advances is described in more detail in Appendix A.2. While the manufacturing of electric planes will lead to higher emissions compared to traditional planes, the impact is expected to be minor since the carbon footprint of battery manufacturing is expected to be significantly reduced in the low-carbon technologies pathway by the time that electric planes take a significant share of the market (Morfeldt et al., 2021).

The total carbon footprint is the result of the energy use (see Section 2.3.1), and carbon intensity associated with energy system transitions (see Section 2.3.2).

2.3.1. *Energy use*

The total energy use was estimated based on mode-specific energy use and travel volumes. Specific energy use estimates were assumed for each mode of transportation (Table 2) and used in combination with assumptions on technological shifts in aviation and railway transportation, see details in Appendix A.2.

The specific energy use of planes was assumed to decrease by 0.96–1.16% per year depending on the decarbonization scenario (Åkerman et al., 2021). Specific energy use for trains is based on estimates from the EU project FINE1 (Iraklis, 2018) – high-speed trains (~250 km/h) for day trains (corresponding to average energy use for regional trains) and intercity trains for night trains. The number of passengers per railcar was assumed to be half for night trains to account for the lower effective spaces per vehicle (Bird et al., 2017), assuming an average railcar – equivalent to a 3-berth sleeper without a private bathroom (i.e., 38 spaces per 26-m vehicle, which can be compared to 76 seats for an equivalent day train). The specific energy use of trains was assumed to decrease by 2.25% per year in the *low-carbon technologies* scenario, which is equivalent to the proposed policy target of halving specific energy use by 2050 (European Commission, 2017). Reductions in specific energy use of 25–35% could be achieved by brake regenerative measures, eco-driving and improvements in comfort functions – all measures with short payback time available for existing systems (González-Gil et al., 2014). Digitalization could enable further optimization of rail operations and timetables, providing potentials for energy savings of up to 35% (Scheepmaker et al., 2017; UIC-IEA, 2019). Specific energy use for diesel-powered trains is assumed to be three times higher than for electric trains (UIC-IEA, 2016) and to follow the same efficiency trajectory as electric trains in the *low-carbon technologies* scenario. Note that diesel-powered trains were assumed to be phased out in the *low-carbon technologies* scenario.

Table 2
Data sources and estimates: specific energy use (reference year 2019) by transport mode.

Mode	Specific energy use	Source
Plane (liquid fuels)	352 W h/pkm*	(Åkerman et al., 2021; Schäfer et al., 2016)
Plane (electric)	180 W h/pkm	Schäfer et al. (2019)
Day train (electric)	45 W h/pkm	Iraklis (2018)
Night train (electric)	76 W h/pkm	(Bird et al., 2017; Iraklis, 2018)

(Note: * = 360 W h/pkm for 2017, with 1.1% efficiency improvements).

[4] Note that this regulation was still under negotiation within the EU at the time of writing.

2.3.2. *Carbon intensity*

The carbon intensity for energy use and battery manufacturing was estimated for each year based on the decarbonization pathway of each part of the energy system (i.e., electricity generation, fossil fuel production and use, production of alternative renewable fuels and use) and battery manufacturing. The carbon intensity of electricity generation was estimated based on current statistics on the average electricity mix and on official scenarios for Sweden and the EU, for the respective decarbonization pathways and years (European Commission, 2018; European Environment Agency, 2021; Swedish Energy Agency, 2021; Swedish Environmental Protection Agency, 2020; European Environment Agency, 2020; Swedish Government, 2020). The carbon intensities used for electricity represent averages for each respective geographic area following the attributional nature of the chosen prospective lifecycle assessment framework (Arvidsson et al., 2018; Yang, 2016). Specific assumptions on the carbon intensities of electricity generation, including estimations of their upstream emissions, as well as assumptions on lifecycle emissions for fossil fuel production and use, the production of alternative renewable fuels and use, and battery manufacturing are described in Appendix A.3.

3. Results

This section presents the results, in terms of annual travel demand, annual carbon footprint and cumulative carbon footprint, for the four scenarios as well as their corresponding decarbonization pathways. The results are initially presented at an aggregate level (Sections 3.1 and 3.2) and then in more detail for four cases, showing the impact of each scenario on a trip from Stockholm (Sweden) to four different destinations: three international and one domestic (Section 3.3). Detailed results are available in Appendix B for the different components of the carbon footprint and all destination countries from Sweden, as well as an analysis testing the sensitivity of the price difference between flights and train journeys on air travel demand and the cumulative carbon footprints.

3.1. *Travel demand: night train demand is sensitive to the number of transfers and ticket prices*

The total travel demand is expected to increase in the period 2025–2050, following historic per capita trends and population growth. Although the development in the short-term (until 2025) is uncertain and depends on the post-pandemic recovery, we assumed near-term improvements in the train offering; as a first step, higher comfort level and easier booking already from 2025, and a reduction in travel time due to the new Fehmarn Belt tunnel from 2030. However, the magnitude of this behavioural shift will be different depending on the relative difference in ticket prices as well as the number of transfers needed to reach the destination (Fig. 4). The travel demand by plane is expected to grow from 7.8 to 19 billion pkm between 2019 and 2050 in the baseline travel demand scenario, whereas travel demand by train is expected to grow from 1.6 to 5.4 billion pkm in the same period. The increase in ticket prices for flights, to a level equal to train tickets, is estimated to have a greater impact on travel demand than introducing additional direct train connections (Fig. 4b).

The probabilities of choosing one travel mode over the other for specific origin-destination pairs are constant in 2025–2030. Travel demand shifts from night trains to flights are based on the estimation of the

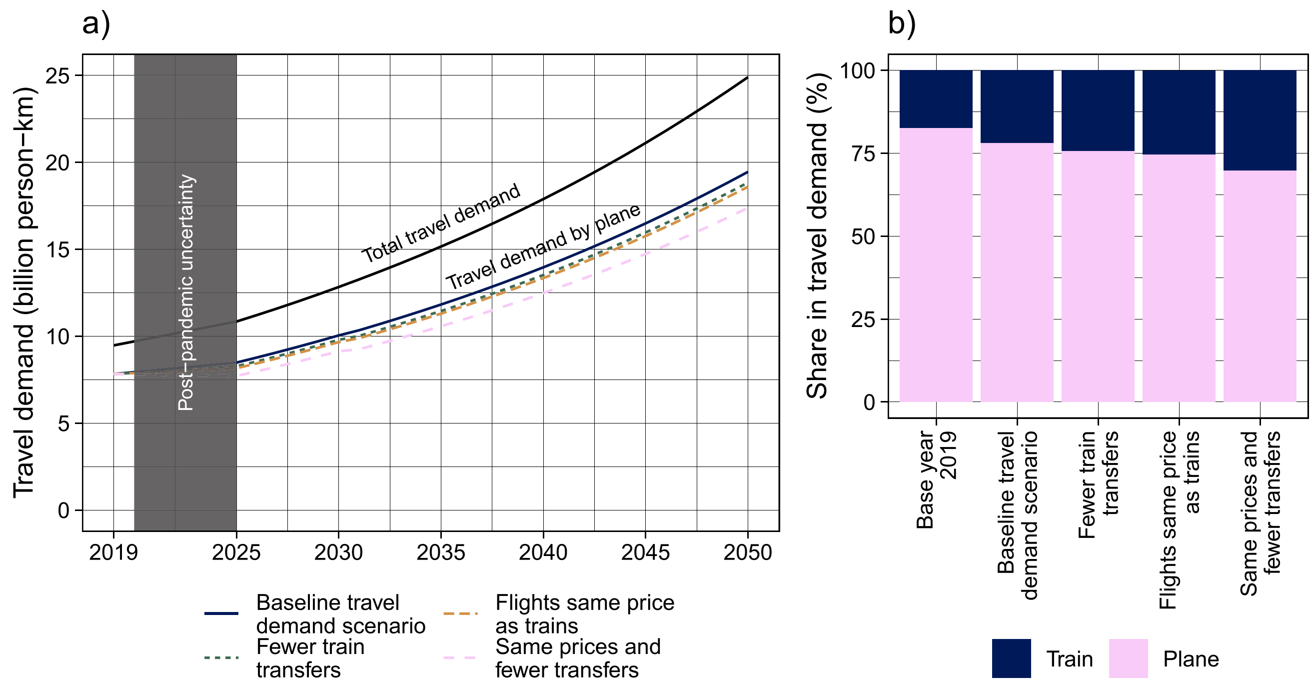

Fig. 4. Scenarios for a) total travel demand (plane and train) and travel demand by plane 2019–2050, and b) shares of travel by planes and trains in total travel demand 2030–2050. Results are given for Swedish tourism (outbound, inbound, and domestic tourism for leisure trips of at least 2 overnight stays).

discrete choice model (Table A.1 in the Appendix) from 2030 onwards, after the opening of the new Fehmarn Belt tunnel (Fig. 4b). In the baseline travel demand scenario, 22% of travellers are estimated to choose train journeys over flights. This share increases for scenarios with fewer train transfers and a similar price for flights as for train journeys, reaching a level of 30% from 2030 onwards, when the two measures are combined. These results are averages and the travel demand by train shares are higher for short trips and lower for long trips. Results for specific origin-destination pairs are illustrated in Fig. 5.

In the base year 2019 (blue dots in Fig. 5), many connections are almost completely serviced by planes. The introduction of new comfortable trains and the opening of the Fehmarn Belt tunnel (the

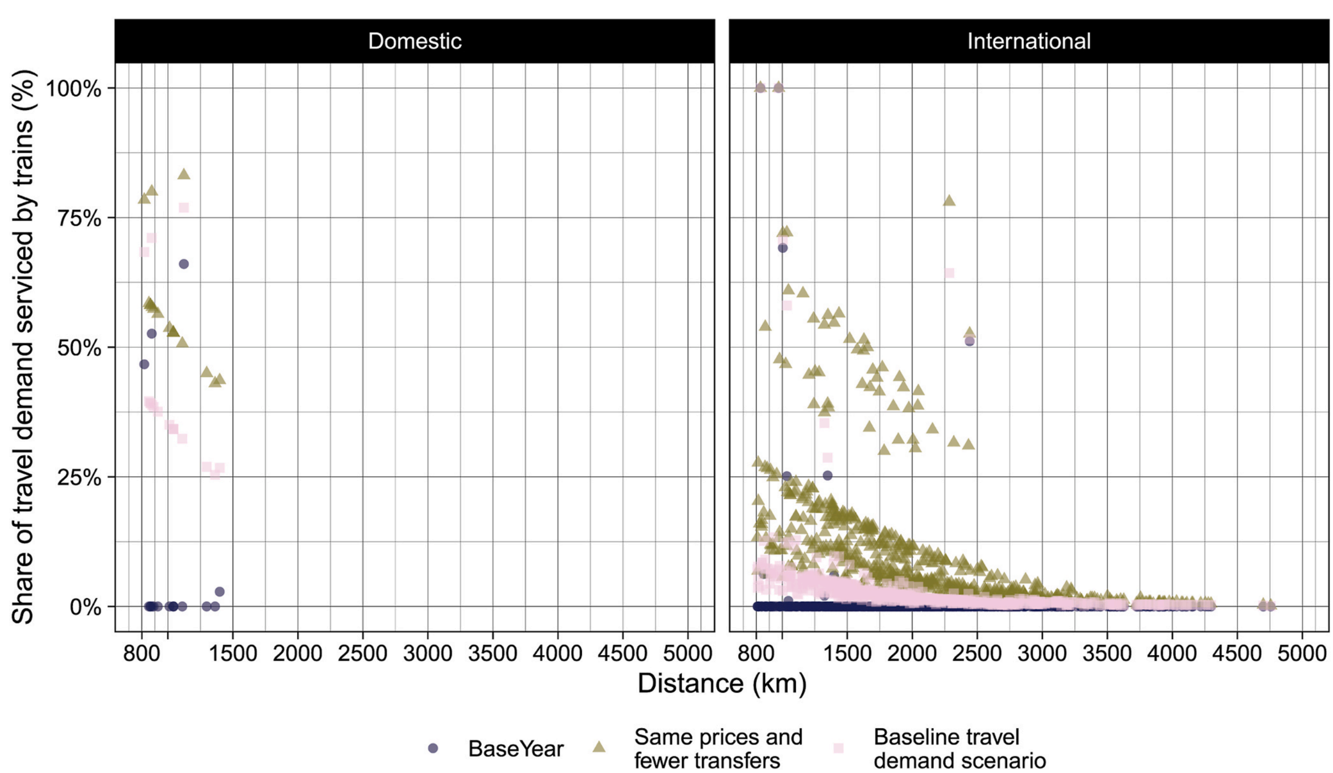

Fig. 5. Share of travel demand (y-axis) serviced by train for origin-destination pairs by distance (x-axis) for the base year, the baseline scenario and similar prices and fewer transfers scenario (shapes). The right panel shows international connections, and the left panel shows domestic connections.

baseline travel demand scenario, pink squares in Fig. 5) is expected to increase the share of trips by train post-2030. For this scenario, the share of travel demand serviced by train for international connections are below 10% for most origin-destination pairs. The scenario with a higher number of direct connections and similar prices for flights and train journeys (green triangles in Fig. 5) would increase the share of travel demand serviced by trains to above 25% also for several international connections. Note that 25% is the critical level at which norm-driven behavioural changes have been shown to be triggered (Centola et al., 2018), see discussion in section 4. Travel demand by night trains is also shown to be sensitive to air travel ticket prices becoming significantly more expensive than train ticket prices (Fig. B.4a in Appendix B). The results suggest that the travel demand serviced by trains could be increased by just over 50% if flights were to become 50% more expensive than train journeys.[5]

3.2. Carbon footprint: decarbonization has a larger impact than mode shifting

The carbon footprints associated with the scenarios depend on the green transition of energy and transport systems in response to future climate change mitigation policies. The results show that the impact on the carbon footprints of decarbonization in line with the Paris Agreement, the *low-carbon technologies* pathway, is significantly larger than that of the mode shifts in the modelled scenarios. In fact, none of the modelled changes would lead to carbon footprint reductions in absolute terms if the energy and transport systems continue to develop in line with *current technology trends* (see Fig. 6a). Nevertheless, the adoption of both fewer transfers and similar price levels for train journeys and flights could further reduce the carbon footprint by around 9% in 2050.

With *current technology trends*, the carbon footprint is expected to be around 2.0 million tonnes of CO_2 equivalents ($MtCO_2e$) per year in 2050 in the baseline travel demand scenario, which is 47% higher than in 2019 (see Fig. 6a). The carbon footprint for the scenario with fewer train transfers to reach the destination is estimated to 2.0 $MtCO_2e$ per year in 2050 and for equally expensive tickets for the two modes the carbon footprint would be around 1.9 $MtCO_2e$ per year in 2050. The combined effect of the two measures reaches a level of 1.8 $MtCO_2e$ per year in 2050. The results also suggest that none of the measures to increase the attractiveness of trains alone would lead to an absolute reduction in greenhouse gas emissions for the post-2025 period.

With *low-carbon technologies*, as a result of a climate policy regime in line with the Paris Agreement's goals, the carbon footprint in the baseline travel demand scenario could be gradually decreased from 2035 onwards reaching 0.72 $MtCO_2e$ per year in 2050. The scenarios with fewer transfers and equally expensive tickets each result in a slight decrease in the annual carbon footprint reaching 0.69 $MtCO_2e$ per year in 2050, whereas the combination of the measures achieves a level of 0.65 $MtCO_2e$ per year in 2050. The carbon footprint is an aggregate of emissions from both train and plane travel, mainly in the form of direct emissions, non-CO_2 radiative forcing and emissions from fuel production, (see Fig. B.1 in Appendix B). The decarbonization pathway would cause some emissions from battery manufacturing but overall emissions reductions are achieved by strong reductions in direct emissions and non-CO_2 radiative forcing.

The cumulative carbon footprint over the period 2025–2050 for the baseline travel demand scenario reaches 28−40 $MtCO_2e$ (see Fig. 6b), depending on the decarbonization pathway, where the lower and higher values represent pathways with *low-carbon technologies* and *current technology trends*, respectively. The two scenarios, fewer train transfers and an equal price for night trains and flight options, individually have relatively low impacts on the cumulative carbon footprint (3–4% reduction compared to the baseline travel for the two scenarios respectively). In combination, the fewer train transfers and equal ticket pricing achieves a decrease in the cumulative carbon footprint of 9% irrespective of decarbonization pathway. Assuming current technology trends, the cumulative carbon footprint could decrease from 40 to 37 $MtCO_2e$, depending on scenario. If climate policies are also assumed to promote low-carbon technologies, the cumulative carbon footprint could be reduced from 28 to 25 $MtCO_2e$, depending on scenario.

The cumulative carbon footprint is heterogenous across destination countries (Fig. B.2 in Appendix B), with destinations in France being the most favourable for introducing measures to incentivize night trains to reduce carbon footprints. The analysis of the modelling framework's sensitivity to the price difference between tickets for air travel and train journeys shows strong reductions in the carbon footprint when assuming that ticket prices for air travel become significantly more expensive than ticket prices for train journeys.

Note that the cumulative carbon footprint presented here includes non-CO_2 radiative forcing as well as short-lived climate forcers (e.g., methane and contrail formation) that have shorter durations in the atmosphere as compared to CO_2 (Lee et al., 2021). Hence, the cumulative carbon footprint should not be seen as an indicator for global warming but rather as a measure to summarize greenhouse gas emissions over the period 2025–2050 using global warming potentials with a 100-year time horizon.

3.3. Four destinations highlight the differences in the impact

To illustrate the impact of the scenarios on travel demand and carbon footprint, we highlight four cases for tourism between Stockholm (Sweden) and London (UK), Barcelona (Spain), Berlin (Germany) and Luleå (northern Sweden). The international destinations illustrate the impact for frequently visited destinations at different distances where night trains might replace flights. The fourth destination illustrates the impact for domestic travel to a city in the far north of Sweden that is connected by night trains as of 2022.

The results for London and Barcelona confirm the aggregated results, where the shares in travel demand show a slight shift towards trains when fewer train transfers are assumed and the price of flights and train journeys are equal (see the top row in Fig. 7). When the two measures are combined, the shift is more significant. For Berlin and Luleå, the shift in travel demand shares towards trains is only a result of changes in the price difference between flights and train journeys since the direct connection is already considered in the baseline scenario. The results also show the cumulative carbon footprint over the period 2025–2050 (see the bottom row in Fig. 7), which highlights that the impact is more significant for destinations with high absolute levels of travel demand and significant potential for mode shifts, such as the trip from Stockholm to London.

4. Discussion

Travel demand is expected to increase in the future but Swedish residents seem fairly willing to reduce the associated climate impact by choosing closer destinations and adopting more sustainable transport modes (Kamb et al., 2020). In this section, we discuss the main results obtained from the analysis of a mode shift from flights to trains. We also provide some recommendations on potential policy interventions for reducing the carbon footprints of long-distance travel and highlight the limitations of the study and topics for future research.

Our results show that up to 30% of total air and railway travel demand could be served by trains under the proposed scenarios as a result of introducing innovations for destinations where this is possible. Those innovations include more comfortable trains, fewer train transfers, and

[5] Note that the estimates shown in the sensitivity analysis are obtained by extrapolating price preferences, meaning that price sensitivity has been applied to prices outside of the tested boundary levels. Therefore, demand changes in response to extreme price differences from the baseline travel demand scenario should be viewed with caution.

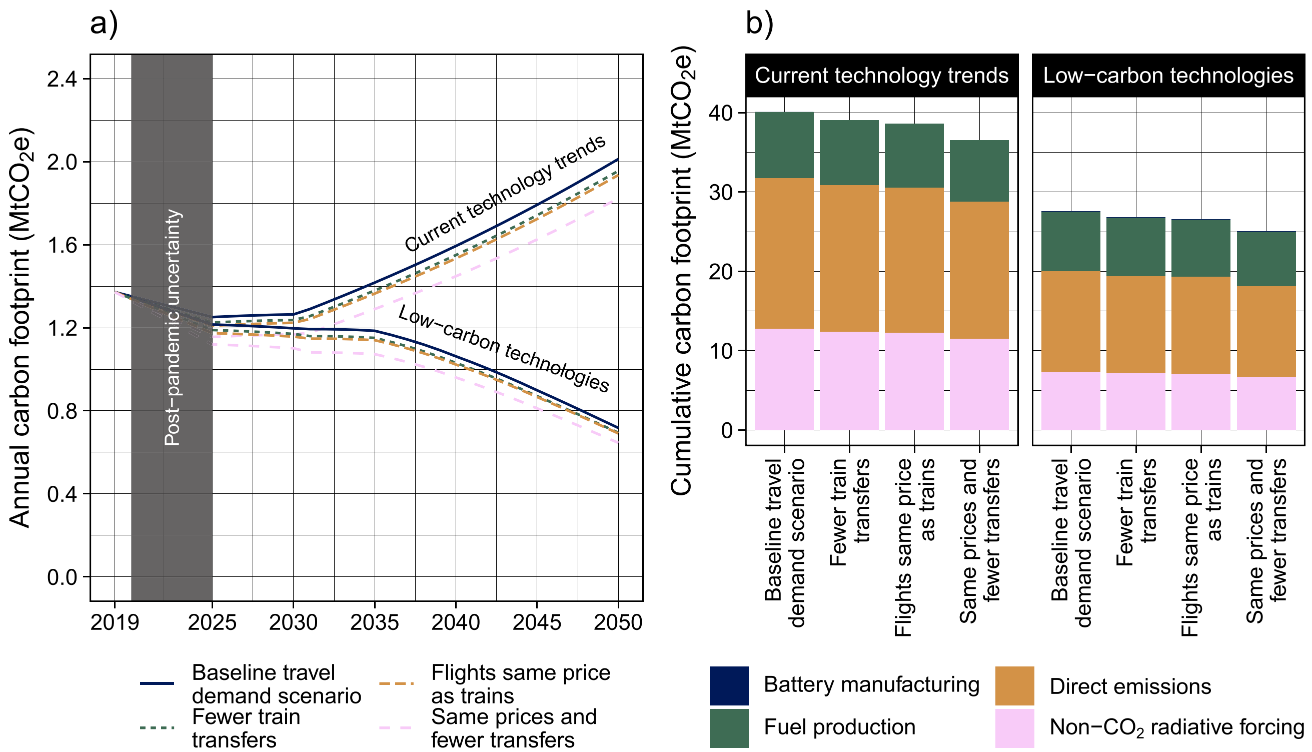

Fig. 6. A) Annual carbon footprint for modelled scenarios for the period 2019–2050. Sweden (outbound, inbound, domestic). b) Cumulative carbon footprint for current technology trends and low-carbon technologies in line with the Paris Agreement's goals.

shorter travel times. The share of travel demand that can be serviced by trains is heterogeneous depending on the scenario and distance of the trip. The increase in train shares is expected to be modest in all scenarios for destinations over 2000 km, but for some mid-range destinations it is expected to reach 25% and over 50% in some strategic corridors, such as in the cases from Stockholm to Luleå or Berlin.

The increasing adoption of night trains could potentially activate norms that have been shown to positively affect sustainable behaviours (Sparkman and Walton, 2017). If such a development were to occur, then larger carbon footprint reductions could be achieved. Experiments have indicated that a threshold of 25% could be a possible tipping point over which a minority may change societal norms (Centola et al., 2018). Hence, reaching a share of trips by train higher than 25% could potentially accelerate a regime change leading to larger mode shifts than what is shown by our results. This share could be reached for several domestic and international connections in a scenario of similar prices for train trips and flights and a higher number of direct connections.

Regarding the associated climate impact, switching from planes to trains specifically could reduce the cumulative carbon footprint by 9% compared to the baseline travel demand scenario. Nevertheless, the annual carbon footprints associated with scenarios following current technology trends in the period 2025–2050 are expected to be higher than in 2019. The results of this study indicate that a significant reduction in the annual carbon footprint, without using low-carbon technologies in aviation, could be achieved through a mode shift from plane to night trains only if the switch is massive. This corroborates evidence from Germany, where changes in travel time and cost of railway options showed a moderate effect on energy consumption and emissions (Nordenholz et al., 2017). A substantial shift could be achieved for example through a strong relative increase in prices for flights. Conversely, the impact on the carbon footprints of low-carbon technologies assisted by following a climate policy pathway in line with the Paris Agreement is significantly larger than the mode shifts in the modelled scenarios. The main drivers for reducing the carbon footprint of Swedish tourism are the measures put in place to reduce the climate impact of aviation.

4.1. *Suggestions for policy interventions*

Policy interventions are needed to meet the goals of the Paris Agreement and some recommendations based on the analysis presented in this study are provided below. Promoting and making night trains more affordable is not enough to decarbonize long-distance travel. Hence, climate policies promoting technological development are essential to reduce the carbon footprint associated with long-distance travel.

A reduction in air travel volumes is one factor that could contribute to reaching the Paris Agreement's goals. Previous research shows that strong global efforts in technological development combined with halving air travel volumes could enable emissions levels in line with the Paris Agreement's goals for the case of Sweden (Åkerman et al., 2021). In order to implement policies for reduced air travel and to enable flight-limiting societal norms to form, relatively attractive alternatives to air travel must be available. Herein lies the main climate change mitigation benefit of a strong policy focus on improving the night train alternative.

The introduction of a ban on flight connections for short-distance trips could be an option, such as in the case of France (Ledsom, 2020), but the effect would be limited given that the share of total air travel demand for Sweden within this distance range is roughly 2% (Åkerman et al., 2021). Strong government interventions affecting relative prices between air and railway travel potentially could be more effective in increasing the adoption of night trains, as shown in the sensitivity analysis (Appendix A.4).

Another policy option is government subsidies for train connections. This has long been used to secure train connections to northern Sweden, but recently also for establishing direct daily night trains between Stockholm and Hamburg (Swedish Transport Administration, 2022).

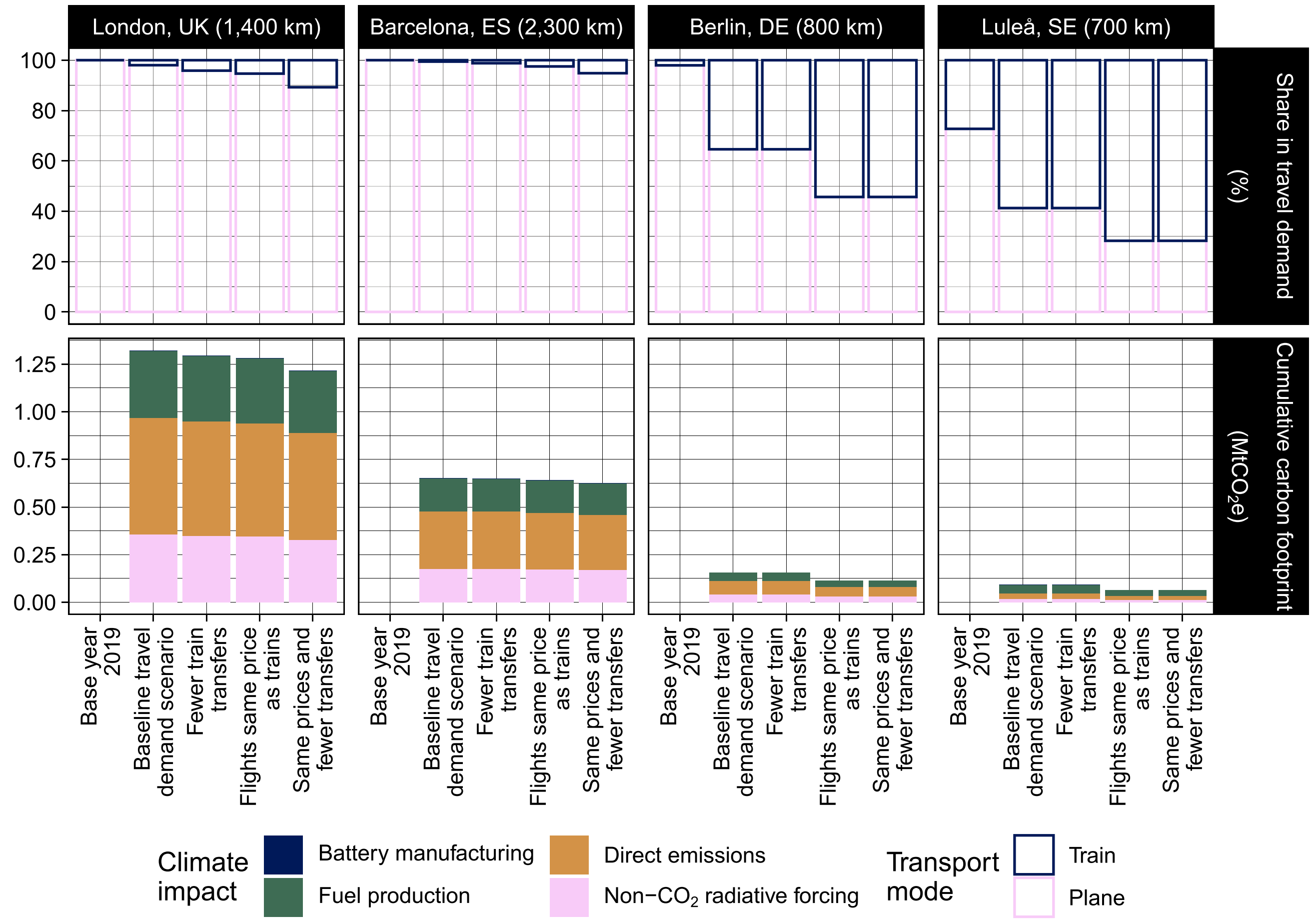

Fig. 7. Impact of tourism between Stockholm, Sweden and four destinations (columns – linear distance from origin in thousands of kilometres) on share in travel demand for each mode in 2050, and carbon footprint (rows). Carbon footprint results assume the low-carbon technologies decarbonization pathway in line with the Paris Agreement. See Fig. B.3 in Appendix B for results related to a current technology trends pathway.

This policy could be expanded for new direct connections, such as from additional Swedish cities and to additional destinations such as Paris. In addition, there are other important policy changes needed, for example, that all EU Member States are open to international subsidized trains and that booking systems and arrival guarantees are customer-friendly (Lena Donat et al., 2021).

4.2. Limitations and future research

This research presents some limitations that can be a guide for future research. First, travel demand data and peoples' preferences come from surveys. They have been collected using rigorous scientific methods, but still suffer from survey-related biases, including selection bias and social desirability bias (Heckman, 1990; Larson, 2019), which could have overestimated the preference for night trains. As the option to give up the intended travel completely when presented with higher prices for flights was not included in the study, this may also contribute to such a bias. Second, the estimations of mode characteristics might be heavily influenced by future technological and legislative changes that are not predictable. We used scenarios and assumptions for unavailable data that were reasonable at the time of writing but may become unrealistic in the near future. While the results for the carbon footprint should be interpreted carefully when assuming extreme variations in the price difference between transport modes, they could motivate further studies on the behavioural response to significant changes in prices. Third, people's preferences are not static and could change in the future for several reasons. Fourth, recent geopolitical events and international sanctions will likely have an impact on European energy policy, which could have relevant impacts on associated carbon footprints related to long-distance travel.

Further research is needed to better understand whether the evidence presented in this study can be generalized also to other countries to inform global climate change mitigation analyses using integrated assessment models. In addition, cost-benefit analyses as well as impact assessments for other sustainable development goals could provide policymakers with enough information to make decisions promoting sustainable travel.

5. Conclusions

This paper aimed to explore scenarios for potential shifts from flights to night trains in long-distance travel and estimate the carbon footprint related to Swedish tourism within Europe. Travel volumes are expected to increase over the analysed period in response to a projected increase in population and the average number of trips per person. The travel demand by plane is expected to grow from 7.8 to 19 billion pkm between 2019 and 2050 in the baseline travel demand scenario, whereas travel demand by train is expected to grow from 1.6 to 5.4 billion pkm in the same period. Hence, 22% of travellers are estimated to choose train journeys over flights from 2030 onwards in the baseline travel demand scenario. This share increases for scenarios with fewer train transfers and similar prices for flights as for train journeys, reaching a level of 30% when the two measures are combined.

The results indicate that progressive night train policies resulting in both fewer transfers and similar price levels for train journeys and flights could lead to transport mode shifts. The mode shifts could result in 9% lower cumulative carbon footprints in relation to a baseline scenario for the period 2025–2050. Assuming current technology trends, the cumulative carbon footprint from Swedish tourism for the period 2025–2050 could decrease from 40 to 37 $MtCO_2e$ through policies affecting ticket prices and the number of train transfers. If climate policies are assumed to also promote low-carbon technologies, the cumulative carbon footprint could be reduced to 28 $MtCO_2e$ in the baseline travel demand scenario and further to 25 $MtCO_2e$ through active train policies. Promoting night train travel could lead to a reduction in the carbon footprint of Swedish tourism, especially if it were to become the norm for travelling to destinations where good night train connections are available. However, even in the "similar price and fewer transfers scenario", which is our most optimistic scenario regarding the attractiveness of night trains, the climate benefits would be much lower than low-carbon aviation technologies, where electric planes and renewable jet fuels become available, and flight routes are changed to reduce non-CO_2 radiative forcing.

Hence, to reduce the climate impact of long-distance travel, night trains represent a solution that is not sufficient per se but, in combination with other changes, (e.g., a trend towards closer holiday destinations and a shift towards renewable aviation fuels), can deliver decarbonized long-distance travel in the future.

CRediT authorship contribution statement

Johannes Morfeldt: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Riccardo Curtale:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Anneli Kamb:** Conceptualization, Funding acquisition, Data curation, Writing – review & editing. **Jörgen Larsson:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Jonas Nässén:** Conceptualization, Funding acquisition, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Methodological detail

Table A.1
Error component model results.

Variables	EC model	
	Est.	(SE)
Choice model		
ASC_{train} (ref = plane)	−0.696	(0.651)
ASC_{Origin}	0.617**	(0.274)
$ASC_{Destination}$	0.617**	(0.274)
Comfort level	1.451***	(0.147)
One change (ref = direct train)	−1.699***	(0.233)
Two changes (ref = direct train)	−2.459***	(0.281)
Travel time (night train)	−0.262***	(0.037)
Travel time (day train)	−0.229***	(0.040)
Travel time (plane)	−0.299**	(0.117)
Travel cost	−0.002***	(<0.001)
Model fit		
Number of individuals	1571	
Number of observations	11,440	
Number of draws	500	
BIC	6403.97	
ρ^2	0.604	

A.1. Travel demand layer – mode characteristics

The travel time values, number of transfers, ticket prices and comfort levels were estimated as follows. The travel time by train was estimated based on travel distances and average travel speed by type of train (night train, day train, and high-speed day train). Travel distances were measured using Google Maps (www.google.com/maps) and the information about the reduction in travel distances after 2029 following the construction of the Fehmarn Belt Fixed Link (Fehmarn Belt tunnel) was retrieved from the German Government (Federal Ministry of Transport and Digital Infrastructure, 2021). The average speed was calculated based on 16 current railway connections (Table A2), resulting in an average speed of 75 km/h for night trains during the night and of 121 km/h during the day. The slower average speed during the night is due to night maintenance of railways and priority for freight transport (Lena Donat et al., 2021). Where available, high-speed trains with an empirical average speed of 178 km/h were considered. When transfers are involved, an average transfer time of 45 min was assumed. For the number of transfers, we considered direct connections, one, two or more transfers depending on origin-destination pairs. For prices, we considered a reference price level depending on distance ranges, and a relative change in the flight ticket price compared to night train journeys, depending on the scenarios. Origin-destination specific prices were based on prices of around 21,000 flights and 400 land connections (European Commission, 2021d).

Relative changes in flight ticket prices were estimated through Flygresor (www.flygresor.se). Flight prices were collected for direct flights including luggage and possibilities to reschedule. We identified connections where there is a relatively high number of Swedish air travel passengers, and where there are relatively good train options which include a night train (from Stockholm, Gothenburg or Malmö to Paris, London, Amsterdam, Vienna, and St. Anton – a popular Austrian ski resort). Prices were collected for trips 5 months in the future and for the month of July, which is the most common annual holidays month in Sweden. Both low-cost and standard airlines were included. Train prices were supplied by the booking agency, Resebutik (www.resebutik.se) and include interrail pass (4 days of travel) and the cost for a bed in a 3- or 4-person compartment (i.e., mid-range option). The average costs for travel to/from airports and train stations were also included. An analysis of the collected data showed a 30% higher price for night trains compared to flights, which has been used in the baseline travel demand scenario. In the altered scenario, equal price levels for night trains and flights tickets were considered. As for comfort level, we assumed that new, comfortable night trains will be available on the market by 2025.

Table A.2
Train corridors.

Train	Corridor	Distance	Travel time	Average speed	Company
DT	Paris-Munich	850 km	5:50 h	146 km/h	SNCF
DT	Amsterdam-Zurich	816 km	7:46 h	105 km/h	OBB nightjet
DT	Zurich-Hamburg	845 km	7:37 h	111 km/h	SBB
DT	Zurich-Milan	280 km	3:17 h	85 km/h	SBB
HS	Paris-Lyon	466 km	1:58 h	237 km/h	Oui
HS	Paris-Marseille	775 km	3:21 h	231 km/h	Oui
HS	Berlin-Munich	620 km	4:26 h	140 km/h	DB
HS	Milan-Rome	580 km	3:00 h	193 km/h	Trenitalia, Italo
HS	Amsterdam-Paris	520 km	3:20 h	156 km/h	Thalys
HS	Madrid-Barcelona	630 km	3:20 h	202 km/h	Renfe
NT	Wien-Rome	990 km	13:37 h	73 km/h	OBB nightjet
NT	Paris-Munich	850 km	9:49 h	87 km/h	OBB nightjet
NT	Paris-Milan	850 km	10:45 h	79 km/h	Thello
NT	Milan-Rome	580 km	7:57 h	73 km/h	Trenitalia
NT	Amsterdam-Zurich	816 km	11:37 h	70 km/h	OBB nightjet
NT	Zurich-Hamburg	845 km	12:15 h	69 km/h	OBB nightjet

A.2. Carbon footprint layer – Energy use: technology shift in aviation and railway

Technology shifts in aviation – electric planes. Electric planes were assumed to start taking market shares from 2035 and onwards, increasing linearly until reaching 30% of travelled pkm in 2050. Schäfer et al. (2019) estimated that electric planes could service 15% of travelled pkm globally by 2060, assuming that electric planes can service distances up to slightly over 1000 km. Since 30% of the trips analysed in this study fall within this range, a higher share of electric plane service was assumed. Schäfer et al. (2019) use an assumed energy density of 800 W h/kg to estimate the range of future electric planes based on historic trends in increasing energy density of Li-ion batteries. However, these levels are unlikely to be achieved using current or improved designed of Li-ion batteries (current Li-ion batteries: 300 W h/kg, advanced Li-ion and solid state: 400–500 W h/kg) and could only be achieved with Li-air batteries (could reach 1350 W h/kg) that are currently at a conceptual stage of development (Su-ungkavatin et al., 2023). Nevertheless, Su-ungkavatin et al. (2023) list promising initiatives using fuel cells, combined fuel cells and batteries, and hydrogen combustion that could be commercially available by 2035, but the information on their lifecycle GHG emissions is currently insufficient. Further, airlines' hub and spoke systems, used today to consolidate passengers in larger airplanes for long haul flights (Pels, 2021), could potentially open for short-range electric airplanes also assuming parts of the travel demand for longer trips. Data collected by Su-ungkavatin et al. (2023) suggests that Li-ion batteries are at the upper end of the range of emissions per unit of energy needed to propel a plane (Li-ion reduces emissions by 37–67% compared to fossil kerosene while some hydrogen options could reduce emissions by 50–100%). Hence, we consider the estimated emissions related to battery manufacturing to be a proxy for other battery- or hydrogen-based airplane designs and should be seen as a conservative estimate.

Technology shifts in aviation – liquid fuels. Planes using liquid fuels were assumed to gradually shift to biofuels/electro-fuels in line with the Swedish emissions reduction obligation quota policy (Swedish Government, 2021b) for flights departing from Sweden (i.e., the carbon intensity of the fuel used should be reduced by 27% in 2030, equivalent to a 34% share of alternative fuels). For the *low-carbon technologies* pathway, it was assumed that the proposed regulation for sustainable aviation fuel (European Commission, 2021c) would be adopted, resulting in an emissions reduction obligation quota policy (i.e., the share of alternative fuels would be 5% in 2030 and 63% in 2050) for all flights departing within the EU. For domestic flights in Sweden, the reduction obligation quota was assumed to increase in the decarbonization scenario, reaching 100% in 2045 in line with the adopted net-zero target (Swedish Government, 2020).

Technology shifts in railways. Swedish passenger train operation is assumed to be 100% electric for the travel demand included in the model. For trains operating in other European countries, 80% of the passenger travel is assumed to be electric and 20% diesel-powered based on the European average for 2019 (European Commission, 2017), which shifts to electric by 2050 in the *low-carbon technologies* pathway in line with proposed policy targets (European Commission, 2017).

A.3. Carbon footprint layer – Carbon intensity: Electricity generation, fossil fuel production, and use, production of alternative renewable fuels and use and battery manufacturing

Electricity generation. Direct emissions in 2019 for Sweden were based on the total emissions from electricity generation divided by the total end-use of electricity (Swedish Energy Agency, 2021; Swedish Environmental Protection Agency, 2020) and were assumed to decrease to zero by 2045 in both climate policy pathways given the adopted climate targets and intentions stated by the Swedish Government (Swedish Government, 2020). Direct emissions in 2019 for the EU were based on the average greenhouse gas intensity for 2017–2019 (European Environment Agency, 2021) and were assumed to decrease in line with scenarios provided by the European Commission (2018), reaching zero by 2058 when the cap on the EU's emissions trading scheme reaches zero. Note that distribution and transmission losses were accounted for in the carbon intensity. In addition to direct emissions, upstream emissions from the production of fuels and power stations (except for hydro and nuclear power stations due to their long lifetimes) were added using a weighted emissions factor. The weighted emissions factor was considered specifically for an electricity mix and year, based on estimates by Pehl et al. (2017) for different electricity generation technologies for the respective climate policy pathways. Given the attributional prospective lifecycle assessment framework applied in this study, average carbon intensity factors for electricity are preferred. Nevertheless, there is a risk that changes in electricity demand in response to the analysed question could be large enough to affect the carbon intensity of electricity (Harmsen and Graus, 2013). To handle this risk, care has been taken to choose scenarios for background systems (incl. Electricity generation) that match the intended development in the foreground systems. The scenario for electricity generation referenced for the Swedish and European average assumes increased electricity demand following strong electrification not only in transportation but also in industry. The IEA scenarios (i.e., Stated Policies and Sustainable Development) both also account for increases in electricity demand, specifically looking at global trends within industry and electric vehicle deployment.

Fossil fuel production and use. The combustion of fossil fuels was assumed to give rise to 249 g CO_2e/kWh for planes (Schäfer et al., 2016) and 259 g CO_2e/kWh for trains, equivalent to a diesel passenger car (Morfeldt et al., 2021). Upstream emissions for aviation fuel were estimated at 66 g CO_2e/kWh (Schäfer et al., 2016), which is close to the estimate of 63 g CO_2e/kWh estimated for liquid fossil fuels (Masnadi et al., 2018). Liquid fossil fuel production was assumed to decarbonize in the *low-carbon technologies* pathway by realizing emissions reduction potentials in refineries equivalent to 50% of current refinery-related emissions by 2070 (Jing et al., 2020), reaching a level of 54 g CO_2e/kWh by 2050 when combined with upstream emissions related to oil extraction.

Production of alternative renewable fuels and use. Both biofuels and electrofuels are eligible candidates for replacing aviation fuel and diesel used in trains with internal combustion engines, so called sustainable aviation fuels (SAF). However, both routes come with significant challenges in terms of availability of biomass feedstock for biofuels, and need for sustainable hydrogen, renewable electricity and uncertainties in the deployment of carbon capture technologies for electrofuels, as summarized in the technology review by Su-ungkavatin et al. (2023). While upstream emissions for alternative aviation fuels vary significantly depending on the feedstock – in the case of biofuels – and the electricity mix – in the case of electrofuels (Pavlenko and Searle, 2021), we do not set out to model pathways for these alternatives. Instead, we use a proxy for this development – based on currently available biofuel technologies in 2019 that shift to synthetic Fischer-Tropsch fuels to explore the impact of increasing the share of sustainable aviation fuels in the future. For sustainable aviation fuels in 2019, we assumed the average emission factor for hydroprocessed esters and fatty acids (HEFA) using non-edible crops of 138 g CO_2e/kWh, due to the high technology readiness level of HEFA and existing production capacity (Su-ungkavatin et al., 2023). In the *low-carbon technologies* pathway, the emission factor gradually shifts to 30 g CO_2e/kWh by 2070, which is the CORSIA default emission factor for Fischer-Tropsch kerosene based on lignocellulosic biomass and comparable to electrofuels based on alkaline electrolysis, direct air capture of CO_2 and Fischer-Tropsch synthesis (Su-ungkavatin et al., 2023). Direct emissions from the combustion of biofuels and electrofuels were considered to be zero since the emitted CO_2 will be captured and stored again by vegetation or direct air capture. Note that while emissions related to indirect land-use change were excluded in this study, they may be high for biofuels with certain feedstocks and that supply may become significantly limited in the future if regulations are put in place. Alternatives to diesel used in trains in the EU include biodiesel based mainly on rapeseed, used cooking oils and animal fats, and hydrogenated vegetable oils (HVO) based on mainly palm oil. Upstream emissions amounted to 89 g CO_2e/kWh and 50 g CO_2e/kWh in 2019, respectively, and if weighted by quantities results in 83 g CO_2e/kWh (Mellios and Gouliarou, 2021). The weighted carbon intensity was assumed for biofuels use in trains in 2019, that in the *low-carbon technologies* pathway decreases to 18 g CO_2e/kWh by 2070 assuming that Fischer-Tropsch diesel (second generation biofuels from wood feedstocks, based on the average of estimates reported on page 59 in the Annex to Directive 2009/28/EC (European Council, 2009)) gradually replaces current biofuel production.

Battery manufacturing – electric planes. Battery manufacturing was assumed to increase emissions by 3.4 g CO_2e/kWh per passenger-km in 2019. The assumption is based on the range 2–10 g CO_2e per passenger-km by Schäfer et al. (2019), which is based on upstream emissions related to battery manufacturing of 39–196 kg CO_2e per kWh battery capacity. The lower level of 3.4 g CO_2e per passenger-km is chosen considering that current levels of upstream emissions in production of batteries in global average manufacturing are lower – around 75 kg CO_2e/kWh (Morfeldt et al., 2021). The carbon intensity in battery manufacturing is likely to drop as the industry matures, and as electricity generation and raw material production decarbonize. Hence, the factor was assumed to decrease at the same rate as emissions per unit of battery capacity for cars in the *low-carbon technologies* pathway, as estimated by Morfeldt et al. (2021), resulting in a level of 1.1 g CO_2e per passenger-km or 24 kg CO_2e/kWh in 2050. This study did not consider other vehicle-related emissions since they were assumed to be unaffected by the scenarios.

A.4. Carbon footprint layer – Non-CO_2 radiative forcing from combustion at high altitude

Aviation contributes with additional climate impacts on top of its fossil fuel use, such as contrails and changes in cloud cover. In this study, these non-CO_2 effects, in terms of global warming potentials with a 100-year time horizon, are estimated using the same approach as Morfeldt et al. (2023), which is based on Dray et al. (2022), Grewe et al. (2021), Klöwer et al. (2021) and Lee et al. (2021).

$$C_n = \frac{C_c}{1034} \cdot \left(652 \cdot \sqrt{1 - \min(S_{SAF}, 0.9)} \cdot (1 - k \cdot S_{Dir}) + 163 + 11 \cdot (1 - 0.74 \cdot S_{SAF}) - 84 \cdot (1 - S_{SAF}) + 23 \cdot (1 + 0.09 \cdot S_{SAF})\right) \tag{A1}$$

where C_n is the additional global warming potential over a 100-year time horizon (GWP-100) from non-CO_2 radiative forcing from combustion at high altitude, as presented in Lee et al. (2021), C_c are the CO_2 emissions from combustion of aviation fuel, S_{SAF} is the share of sustainable aviation fuels (SAF) in the fuel, $k = 50\%$ is an assumed constant for how effective changes in flight paths to avoid formation of contrails are in reducing the climate impact, and S_{Dir} is the rate of implementation for changes in flight paths to avoid formation of contrails.

The first term $(652 \cdot \sqrt{1 - \min(S_{SAF}, 0.9)} \cdot (1 - k \cdot S_{Dir}))$ represents the CO_2-equivalent contribution of aviation induced cloudiness (AIC) and is based on Klöwer et al. (2021) with a modification, based on Grewe et al. (2021), that accounts for that contrails may still be formed even when the emitted condensation nuclei become very small. The second term (163) represents the CO_2-equivalent contribution of NO_x emissions (assumed to be similar for SAF and fossil jet fuel), the third term $(11 \cdot (1 - 0.74 \cdot S_{SAF}))$ represents the CO_2-equivalent contribution from soot emissions (assumed to be 74%

smaller for SAF than fossil fuels), the fourth term $(84 \cdot (1 - S_{SAF}))$ represents the cooling from sulfur aerosols (assumed to be negligible for SAF), and the fifth term $(23 \cdot (1 + 0.09 \cdot S_{SAF}))$ represents the CO_2-equivalent contribution from water vapor (assumed to be 9% larger for SAF than fossil jet fuel due to the slightly higher hydrogen content in SAF), all based on Dray et al. (2022).

The rate of implementation, S_{Dir}, is assumed to follow an S-curve reaching 100% in 2070 for the *low-carbon technologies* pathway while it is assumed to be 0% in the *current technologies trends* pathway. The developments of the share of SAF in the different scenarios are described in Appendix A2.

Appendix B. Detailed results

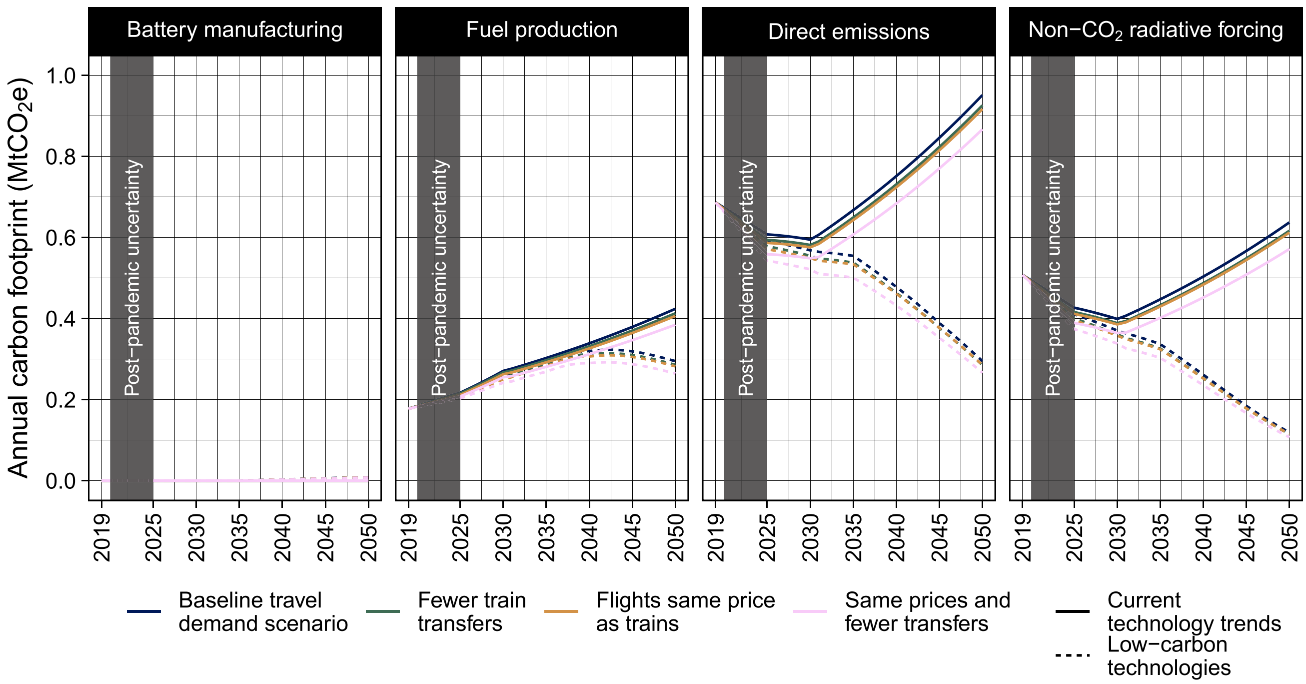

Fig. B.1. Annual carbon footprints associated with battery manufacturing, fuel production, direct and non-CO_2 radiative forcing.

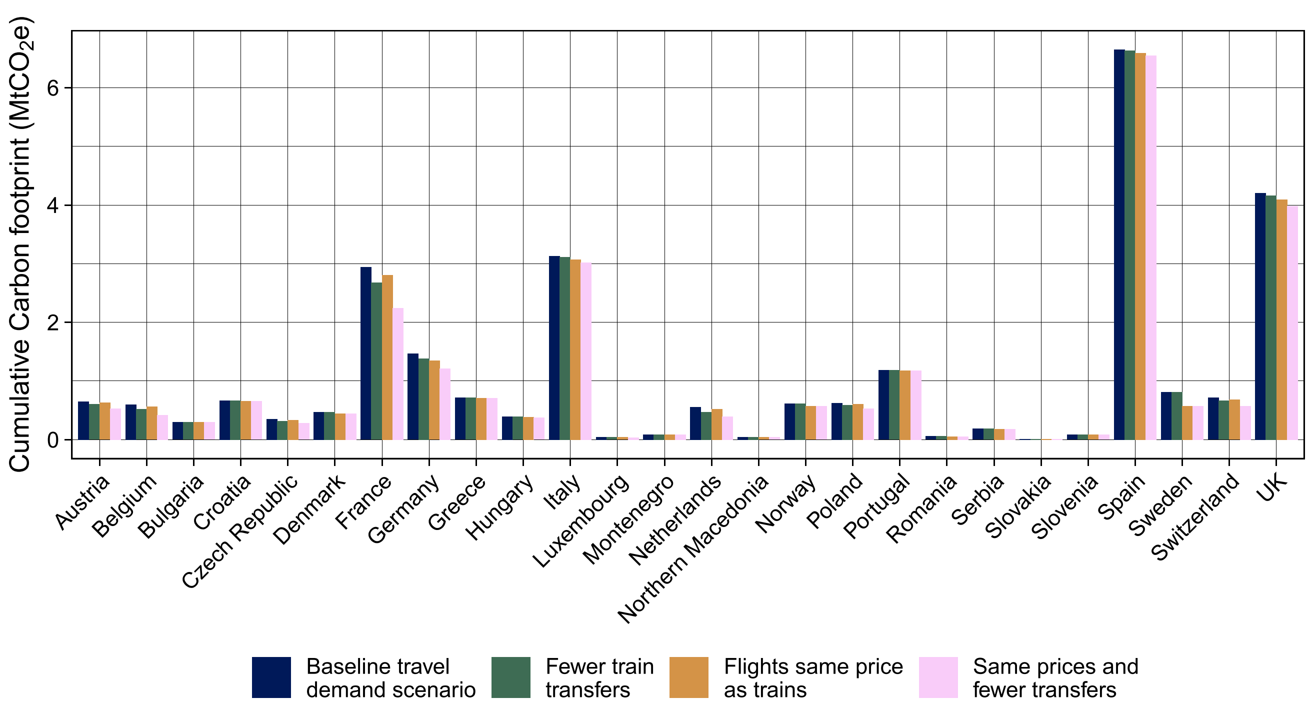

Fig. B.2. Cumulative carbon footprint 2025–2050 assuming decarbonization in line with Sustainable Development, by country and scenarios.

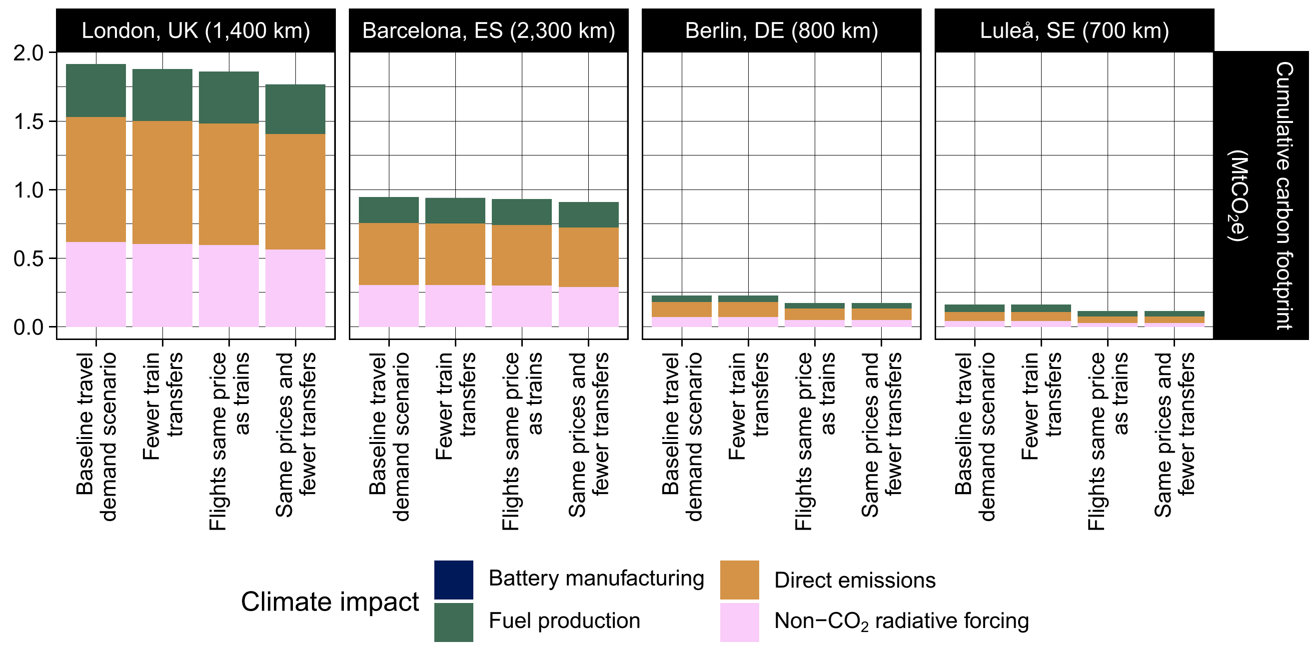

Fig. B.3. Impact of tourism from Stockholm, Sweden to four destinations (columns – linear distance from origin in thousand kilometres) on carbon footprint. The results assume the current technology trends decarbonization pathway.

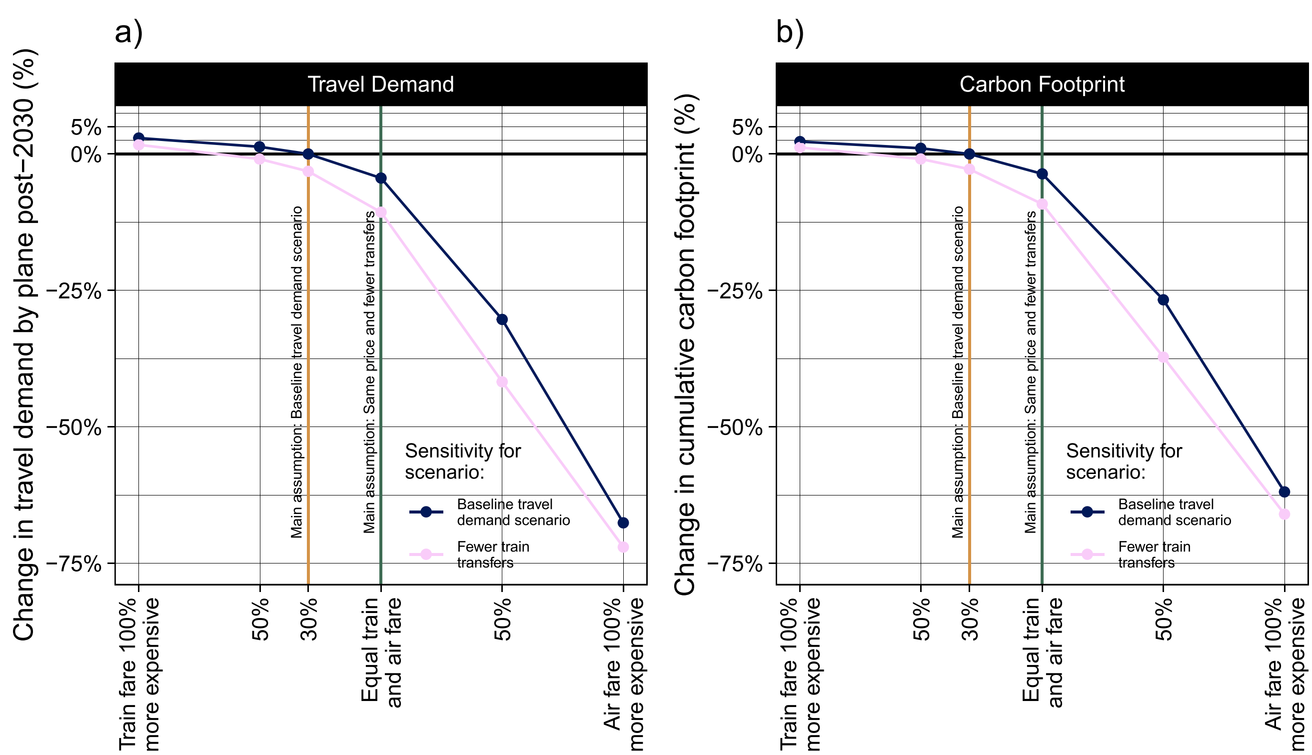

Fig. B.4. Sensitivity analysis of the impact of the ticket price difference on travel demand (a) and cumulative carbon footprint (b). The results for the carbon footprint assume the low-carbon technologies decarbonization pathway. The results for the current technology trends pathway are almost identical and therefore not displayed in this figure.

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