MASTER THESIS

The future impact of the global aviation sector on climate change mitigation unravelled

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Executive summary

The aim of this study is to comprehend how the aviation sector could contribute towards reaching the climate goals as stated in the Paris Agreement of 2015. This is done by exploring the knowledge gaps in the representation of the aviation sector in the Integrated Model to Assess the Global Environment (IMAGE), in which this study is conducted. First, the key drivers of air travel demand are identified, namely income approximated through Gross Domestic Product in combination with population growth. Secondly, the most important emissions mitigation pathways mentioned in scientific literature are reviewed. Through this analysis, several contributors to emission mitigation are identified, namely the usage of sustainable aviation fuels, the introduction of alternative propulsion technologies, the improvement of the efficiency of the fleet, and a modal shift from air travel to high-speed train. Thirdly, this study further explored current literature on technological and economic characteristics of the aviation sector and used this knowledge to update the representation of the aviation sector in IMAGE. This newly improved version of IMAGE was then utilized to develop four different mitigation scenarios, in comparison with a baseline scenario based on SSP2, to identify how demand and technological change contribute to emission mitigation. Additionally, policy targets to reach the climate targets of 1.5 °C' and 2 °C are incorporated in IMAGE to understand how the emissions reduction differ if these restrains are met. The results of the developed scenarios show that alternative propulsion technologies and efficiency improvements have limited effect on emissions mitigation. However, the modal shift to high-speed train can reduce CO_2 emissions considerably, while the greatest reduction potential is achieved if the aviation sector increased its share of bio-fuel in the fuel mix. These results demonstrate the importance of sustainable aviation fuels for emission mitigation. Importantly, however, the scenarios also indicate that net zero emissions are practically unreachable by the end of the century, even if a profound carbon tax in included in IMAGE. It becomes clear that further effort in technology development and additional policies are fundamental to potentially decarbonizing the aviation sector as a whole.

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1. Introduction

In December 2015, the Paris Agreement on climate change was signed by 195 countries, which is aimed at ‘holding the increase in the global average temperature to well below 2 °C’ and ‘to pursue efforts to limit the temperature increase to 1.5 °C’ compared to pre-industrial levels (UNFCCC, 2015). Numerous studies show a variety of pathways to achieve net-zero carbon dioxide (CO_2) emissions around the year 2050 or to some extent thereafter (Grubler et al., 2018; Rogelj et al., 2015, 2016; Tavoni et al., 2015; Van Vuuren et al., 2016). A robust finding across these studies is that a few critical sectors, such as the industry and transportation, are particularly hard-to-abate. Consequently, a potential dilemma could arise, since other sectors are sustained to further increase their decarbonization goals to comprise for this fact, if the climate targets from the Paris agreement are to be achieved. These hard-to-abate sectors are difficult to decarbonize due to different causes, for instance a lack of cost-effective technological reductional potential or barriers implementing these. Meanwhile, a substantial growth in demand for sectoral activity is expected (Loftus et al., 2015; Sharmina et al., 2020). A study by Luderer et al. (2018) demonstrates the role of these hard-to-abate sectors by showing the range of reductions in several sectors of direct CO_2 emissions from fossil fuels and industry. These reductions are based on seven different models, with a likelihood of >67% that the global temperature is below the target temperature of 2°C in 2100. In this scenario, the power sector emissions are reduced by ~90% in 2050 relative to 2010, while for the industry and transportation sector, emissions are only reduced by ~50% and ~5%.

An essential segment of the transportation sector is the aviation sector. It is associated with one of the most-energy intense forms of consumption, characterised by strong historical growth. Between 1960 and 2018, it has been estimated that greenhouse gas (GHG) emissions of the sector have increased by a factor of 6.8 (Gössling & Humpe, 2020; D. S. Lee et al., 2021). However, the International Civil Aviation Organization (ICAO), a United Nations organisation that advises and establishes air traffic standards for 193 countries, assesses that this sector’s emissions could triple between 2020 and 2050 due to an expected growth in air travel activity. Meanwhile, options of implementing low carbon technologies to reduce these emissions are lacking (ICAO, 2019). Although revenue passenger kilometres (RPK) and scheduled flights have declined considerably due to the Covid-19 pandemic crisis, the ICAO expects a rebound in demand as this also happened after earlier crises (e.g. the 2008 financial crisis) (ICAO, 2020). If the aviation sector would resume its volume growth trajectory, it would be in severe conflict with the worldwide decarbonisation goals (Larsson et al., 2019). For that reason, a deeper insight is required to understand how this sector could contribute towards reaching the Paris Agreement climate targets.

Mitigation scenarios, based on integrated assessment models (IAMs), can provide an understanding of consistent global strategies that significantly reduce GHG emissions due to their cross-sectoral, cross-temporal and cross-regional nature (Clarke et al., 2014; Van Vuuren et al., 2018). Therefore, to understand how the aviation sector relates to other sectors in terms of climate mitigation, IAMS are a helpful tool. Several different types of IAMs exists, such as the Integrated Model to Assess the Global Environment (IMAGE). IMAGE is this main model utilized in this study, and is further discussed in Chapter 2: Theory. IAMs describe the key interactions between human development and the environment and help to understand complex, long-term and global issues. IAMs, however, differ in the level of scope and detail assessed. For instance, IMAGE is a partial equilibrium simulation model with much sectorial detail, while REMIND, a global multi-regional economic climate model, is considered as a top-down optimisation model with a special focus on the development of the energy sector on a global scale (Luderer et al., 2015; Stehfest et al., 2014). IAMs are typically used to develop mitigation scenarios to achieve a specific climate target, such as the Paris Agreement's goals (Grubler et al., 2018; Van Vuuren et al., 2018). This is generally done by identifying a cost-optimal mixture of technologies given a set of policy assumptions and the model’s rules on system behaviour (Clarke et al., 2014; Van Vuuren et al., 2016).

IAMs are also helpful to comprehend the relationship between air travel and climate change mitigation. For instance, with the usage of an IAM, Wise et al. shows (2017) that jet fuel produced via bio-energy with carbon capture and storage (BECCS) has the potential to significantly reduce the carbon intensity of the aviation sector without having a substantial impact on bioenergy usage in the rest of the global energy system. Moreover, Girod et al. (2012) have demonstrated that, with a focus on the global aviation sector, the emissions target of 2 °C in the year 2100 can be realised by switching to biofuels or using more efficient airplanes in combination with a modal shift to high-speed trains.

While these studies demonstrate how the aviation sector interacts with climate change mitigation scenarios, knowledge gaps still exist. These studies focus mainly on the usage of biofuels in the sector, while this study goes beyond that. Additionally, IAMs tends normally not to focus on the aviation sector in detail. An explanation of this can originate from the fact that the sector is still relatively small (11.6%) in terms of global CO_2 emissions in comparison with other forms of transport emissions, such as road passenger and freight (74.5%) (IEA, 2018). Yet, many studies show that the aviation sector is one of the fastest growing sources of GHG emissions today, and its emissions are projected to increase sincerely in the future (Dray et al., 2019; Gössling & Humpe, 2020). Furthermore, seeing that an efficient carbon market price mechanism in the sector is lacking, and the Paris Agreement did not make individual countries responsible for their emissions caused by international flights, it has become utterly challenging to achieve net zero emissions in this particular sector (Hasan et al., 2021). For that reason, it is absolutely necessary to understand how climate change mitigation pathways could potentially help to decarbonise the aviation sector.

Moreover, the sector is changing in terms of technology, innovation and activity. For instance, newly developed technologies can expand in the future, such as all-electric or hydrogen-powered aircrafts. It is estimated that all-electric aircrafts, with a flying range of more than 1.100 km, can replace half of the global aircraft departures. Furthermore, all-electric and hydrogen-powered aircrafts are potentially emission-free, but are not technology-ready at the moment (Baroutaji et al., 2019; Goldmann et al., 2018; Schäfer et al., 2019). Therefore, a thorough analysis of recent developments is required to understand the prospects of changes in air travel demand, CO_2 emissions, mitigation costs, and the feasibility of technological options, such as improved aeroplane designs or the usage of sustainable aviation fuels (Girod et al., 2012). Consequently, the question arises how these different technologies will conceivably develop and expand over time. If these aspects are better understood, the representation of the aviation sector in IMAGE can be improved. As a result, a deeper understanding is acquired on how the sector contributes towards achieving the climate goals.

1.1 Research aim

This research aims to understand how the aviation sector contributes to reaching the climate goals as stated in the Paris Agreement of 2015. First, an in-depth analysis of recent developments in technology innovation and activity is conducted. Next, the outcomes of this analyses are used to adapt the IMAGE model thereby improving the representation of the aviation sector. Next, using the updated IMAGE model, this study aims to comprehend how the sector could evolve in the future and how the aviation sector interacts with specific climate goals. For that reason, the following central research question is constructed:

1.2 Research question

> *"How could the aviation sector contribute towards reaching the climate goals as stated in the Paris Agreement of 2015?"*

1.3 Sub questions

a) *What are important drivers of global demand for air travel?*
b) *What are crucial pathways to mitigate emissions in the aviation sector?*
c) *What are the technological and economic characteristics of historical, current, and future aircrafts, and how do they evolve over time?*
d) *How do the demand and technological change in the aviation sector contribute to emission mitigation?*

1.4 Scientific relevance

This study is of scientific relevance since it explores the knowledge gaps in the representation of the aviation sector in IAMs. This knowledge is beneficial for the science of today and the future: it provides a better understanding of the extent to which the aviation sector plays a role in achieving climate targets and how this sector could potentially be decarbonised. This insight will be used to improve the IMAGE model. Consequently, this research relates to the focus of the master Sustainable Development; Energy & Materials track, which aims to analyse energy and materials systems and the transitions to the sustainable use of energy and materials.

1.5 Societal relevance

IAMs, and thus IMAGE, are developed to describe the interactions between the climate system's processes, the biosphere and society to asses sustainability problems such as human well-being, biodiversity, and climate change. To improve such a model contributes towards the knowledge on how these systems interacts. In consequence, this enhanced insight can be exploited by policymakers or other decision-makers to tackle the sustainability issues in which the global society is detained today.

2. Theory

This section elaborates on the concept of IAMs. Also, an overview is provided of the different models with whom this study is conducted. Lasty, the aviation sector is further discussed in detail.

2.1 IMAGE

The analysis of the aviation sector in this research is done using the IAM IMAGE. IMAGE is developed by the Netherlands Environmental Assessment Agency. IMAGE is a comprehensive ecological-environmental modelling framework that simulates the environmental effect of human activities in the long-term (from 1970 up to the year 2100) on a global scale. Furthermore, it describes the key processes between the Earth and the Human system concerning global environmental problems (Clarke et al., 2014; Van Vuuren et al., 2018). The main objectives of IMAGE are (Stehfest et al., 2014):

- "To analyse large-scale and long-term interactions between human development and the natural environment to gain better insight into the process of global environmental change."
- "To identify response strategies to global environmental change based on an assessment of options for mitigation and adaptation."
- "To indicate key interlinkages and associated levels of uncertainty in processes of global environmental change."

IMAGE is developed to be comprehensive in terms of human activities, various sectors and environmental impacts. Moreover, it demonstrates how and where these components are connected through mutual impacts, common drivers, trade-offs and synergies. A schematic outline of the different components utilised in IMAGE is shown in . In this figure, it becomes clear how key drivers, such as population, economies, policies, technology, lifestyle and resources, interact with important components in the Human and Earth system. For example, the energy supply and demand component, in which the description of the aviation sector in IMAGE is embedded, develops outputs in bioenergy production, based on these key drivers, which are then used again as an input in the land-use allocation, described in the agriculture and land use framework.

Additionally, since IMAGE is created to address issues occurring on a global scale, the spatial resolution of the model is of utter importance, since challenges and impacts have a tendency to occur at different geographic scales and also to various gradations in different parts of the world (Stehfest et al., 2014). For example, biophysical conditions or the level of human development (i.e. high income versus low income, or industrialized versus agricultural dictated regions) tend to be location dependent. This suggests that global average indicators are seldom suitable to uncover the real challenges in which humanity is detained today. Therefore, to describe multi-scale and spatial varieties, the socio-economic developments are modelled in 26 different world regions. A representation of this spatial resolution in shown in **Fout! Verwijzingsbron niet gevonden.**.

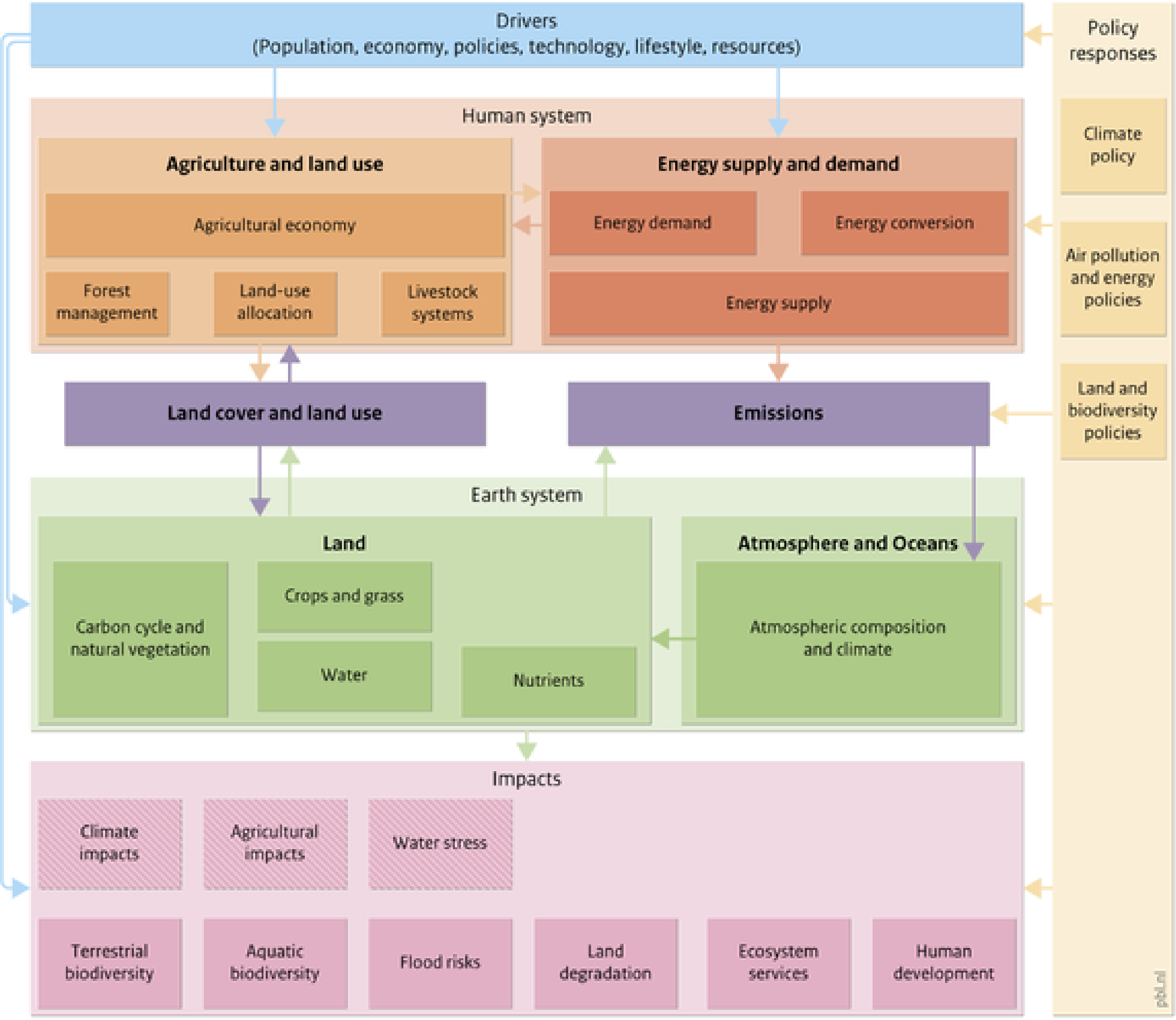

Figure 1 IMAGE 3.0 framework; a schematic summary of the different components (Stehfest et al., 2014)

2.1.1 Shared Socioeconomic Pathways

IMAGE is frequently used to delve into two types of specific problems (Stehfest et al., 2014):

- "How the future unfolds if no deliberate, drastic changes in prevailing economic, technology and policy developments are assumed, commonly referred to as baseline, business-as-usual, or no-new-policy assessment;
- "How policies and measures prevent unwanted impacts on the global environment and human development"

These specific problems are typically analysed by creating baseline and mitigation scenarios based on five Shared Socioeconomic Pathways (SSPs), developed by the climate change research community. The SSPs comprises a narrative description of how the future possibly develops in terms of societal trends, in which a set of assumptions is made for population growth, the rate of urbanisation and economic growth (Riahi et al., 2017). SSP1 (Sustainability - Taking the Green Road) and SSP3 (Regional Rivalry – A Rocky Road) describes futures in which the challenges to mitigation and

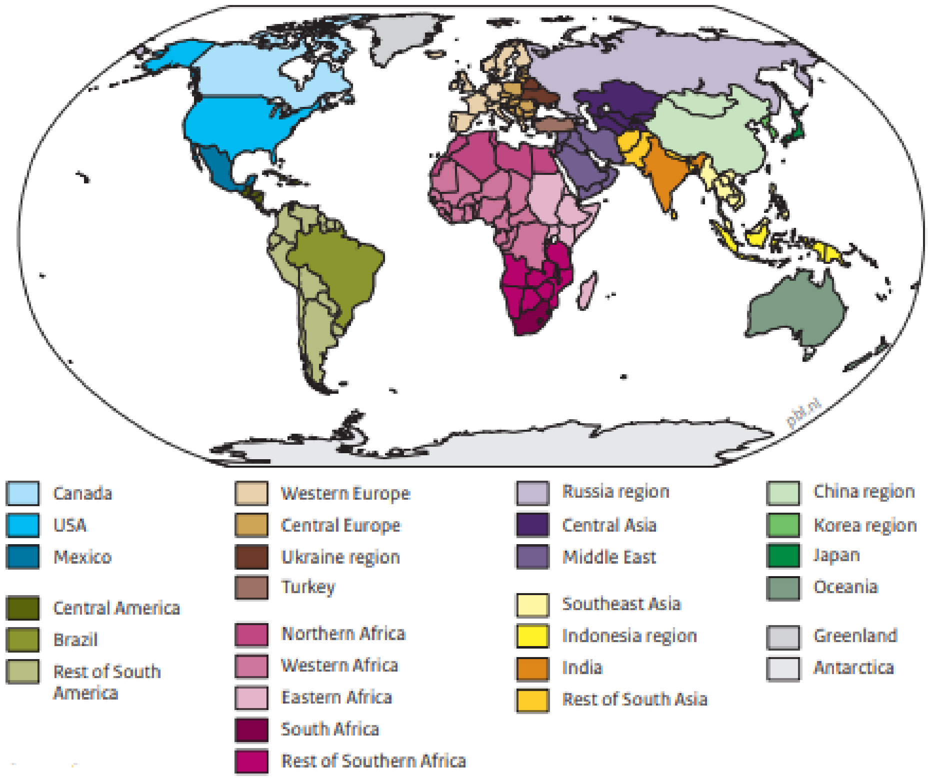

Figure 2: an overview of the 26 world regions utilised in IMAGE 3.0 (Stehfest et al., 2014)

adaptation are marked as low and high, respectively. In addition, SSP5 (Fossil-fuelled Development – Taking the Highway) involves a narrative in which low challenges to adaptation is combined with high challenges to mitigation, while for SSP4 (Inequality – A Road Divided) the opposite is assumed. Finally, the SSP2 (Middle of the Road) describes a world in which the challenges to mitigation and adaptation are defined as intermediate. These SSPs are of importance since they form a extra layer to understand how the future will unfold in the context of climate change projections, when climate change scenarios are developed. Consequently, the SSPs are used to ease the integrated analysis of future climate change impacts, to understand the different challenges on climate adaptation and mitigation (Riahi et al., 2017).

2.2 TIMER

The IMAGE framework is considered as the overall integrated assessment model to analyse the global environmental issues and the sustainability challenges. However, as earlier referred to, IMAGE consists of different components in which various modules interact with one another, based on key drivers, such as population. For example, the energy supply and demand component, shown in **Fout! Verwijzingsbron niet gevonden.** and symbolised by the red box in the Human system module, are described by the The Image Energy Regional model, also referred to as TIMER. This model has been established to develop possible scenarios for the global energy system in the broader context of the IMAGE framework (Detlef Peter van Vuuren, 2007; Vries et al., 2002). This is accomplished by analysing long-term trends in energy supply and demand in the context of sustainability development issues by describing 12 primary energy carriers in 26 different regions, as shown in **Fout! Verwijzingsbron niet gevonden.**.

TIMER consist of three main components: energy demand; energy conversion; and energy supply; The energy demand component is built up to describe how energy demand behaves in five different economic sectors, namely residential, transport, industry, services and other sectors. The energy conversion component describes how energy is converted into other energy carriers and how these carriers, such as hydrogen and electricity, are produced. Lastly, the energy supply component describes the production of different primary energy sources, and it calculates various prices for primary and secondary energy carriers that are driving the investments in the technologies related to these carriers. With these three components the amount of GHG and air pollutant emissions can be calculated.

2.3 TRAVEL

The last and most important model utilised in this study, is a global transport model, called TRAVEL. This model is part of the previous discussed TIMER model. TRAVEL is used to determine how the global transport sector interacts with global environmental issues and thus specific emission targets (Girod et al., 2012). First, a brief summary is given of the model. Secondly, the equations and assumptions utilized in TRAVEL are discussed.

2.3.1 Overview of TRAVEL

The travel module consists of four main modules: the travel modes module, the vehicle module, the fleet module and the policy module. This structure is visualized in **Fout! Verwijzingsbron niet gevonden.**. Subsequently, the model requires inputs variables in a socio-economic context, such as fuel price or income. Moreover, the transport technology specifics, for instance fuel type or energy efficiency, are used as inputs variables in the model. Eventually, these inputs are used to determine global projections regarding various variables, such as CO_2 emissions or travel demand. Additionally, an emission target can be included as an input. For example, the 1.5 °C target as stated in the Paris Agreement, which then interacts via the policy module with the other three modules. These inputs define the outcome in global projections, so comparisons between policies or non-policies induced scenarios can be made. However, for this study, the policy module is not incorporated in this way. To understand how the aviation sector relates to climate change mitigation pathways in relation to the climate targets of the Paris Agreement, input of the climate policy model FAIR is used (Stehfest et al., 2014). This input consists of a carbon price in 2005 US$ in tonne per C-equivalent, and is derived to reach climate targets defined in terms of concentration levels, temperature, radiative forcing, and cumulative emissions. Consequently, this carbon price is utilized as in input in TRAVEL and acts as a replacement of the policy module.

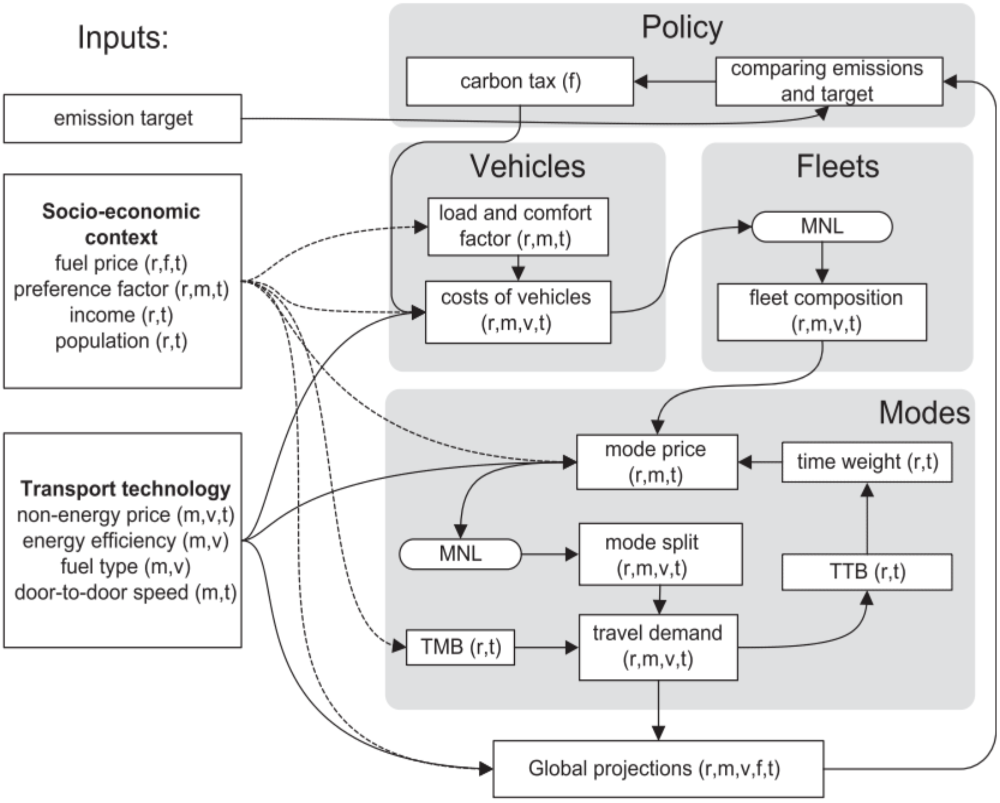

Figure 3: A schematic overview of the TRAVEL model, where the indices *r, m, v, f, t,* stands for denote region, travel mode, vehicle type, fuel type and time, respectively (Girod et al., 2012).

The *travel mode module* describes how the travel volume of seven different travel modes (aeroplane, high-speed train, rail, car, foot, bicycle and bus), are formed in the earlier mentioned 26 regions. There are two fundamental rules that determine how the mode split of the travel module is utilised: the travel-time budget (TTB) rule, and the travel-money-budget (TMB) rule. The TTB is based on the estimation that it approaches 1.2 hour per day on a global scale. Some studies suggest that the TTB remains constant in the future (Schäfer et al., 2010), while others argue an annual increase of TTB by 2 min per day (Toole-Holt et al., 2005). For this study, the middle road is taken, and an annual increase of TTB by 0.25 per day is assumed. The TMB is estimated as 12% of GDP (Schafer et al., 2010). Both rules are crucial for describing the transitions processes within the seven different travel modes, while their speed characteristics, their relative costs, and consumer preferences for comfort and specific transport modes are taken into consideration. Furthermore, within the module, the TMB and TTB are combined with a multinominal logit (MNL) type equation, which is further explained in section 2.3.2. Moreover, the travel mode module also describes how the travel volume of six different freight modes (medium and heavy truck, national and international shipping, train and aviation) are structured.

The *fleet module* describes how different specific technologies within a travel mode, such as the car, are competing with one another. For example, the module within the mode 'cars' consist of 22 different technology types, such as the hybrid electric vehicle or the conventional internal combustion engine.

Based on MNL type equations for new investments and a structure for existing stock, the market share of each technologies within a mode is determined.

The *vehicle module* describes the cost, the speed and the efficiency of the different transportation vehicles. Lastly, with the input of FAIR, a carbon tax affects the costs in the fleet-composition module, as in the travel-mode module, by increasing the costs of carbon-based fuel prices. This usually results in lower emissions (more usage of efficient technologies; switch to less energy intensive transport modes; more usage of low or zero carbon fuels). In addition to these modules, assumptions on energy prices, population and income are included in TRAVEL and applied as inputs variables. This data is derived from the connected IMAGE-TIMER model (Girod et al., 2012).

2.3.2 Equations and assumptions of TRAVEL

TRAVEL is driven by a set of constrains, such as the TMB, TTB. Furthermore, it is assumed that the lowest travel-cost technology is preferred, which forms the basis of the modelling method. As earlier mentioned, some modes are dependent on MNL type equations. The advantage of these equations, is the ability to assign market shares to a number of different technologies, while having dissimilar travel costs, since this is frequently through empirical observation noticed (Girod et al., 2012). An example of an MNL-type equation is shown in Equation 1:

$$Share_{i,t} = \frac{\exp\left(\lambda * Cost_{i,t}\right)}{\sum_i \exp\left(\lambda * Cost_{i,t}\right)} \tag{1}$$

where λ is the calibration factor that determines the sensitivity of the shares to the different cost for a vehicle or mode *i*, which varies over time *t*. The determination of the fleet composition *(VehicleShare),* and the mode split, as shown in Figure 3, are established with a MNL type equation.

To model the travel mode (*m*) shares for each region (*r*) over time (*t*), a constant factor, the real costs, and the costs related to travel time are considered. This relation is shown in Equation 2:

$$Cost_{r,m,t} = Const_{r,m,t} * CostPerPkm_{r,m,t} + Timeweight_{r,m,t} * TimeUse_{r,m,t}\ [-] \tag{2}$$

Where the constant (*Const*) is used to correct for non-monetary differences between the travel modes. The time weight (*Timeweight*) describes the difference between monetary costs and the value of time. While, the time use is defined on the door-to-door speed of the different travel modes, derived from scientific sources (Girod et al., 2012).

The fleet composition of a travel mode (*VehicleShare*) is determined with a second MNL equation. Here, it is assumed that the monetary cost is the decisive component and it consists of three different factors:

$$CostPerPkm_{r,v,t} = \frac{AddTechCosts_{v,t} + EnergyCosts_{r,v,t} + NonEnergyCost_{r,t}}{load_{r,t}}\ [\frac{USD}{pkm}] \tag{3}$$

Where the additional technology costs (*AddTechCosts*) describes the relative investment required, compared to the baseline vehicle, to achieve more efficient vehicles. The energy costs (*EnergyCosts*) are based on the efficiency of the vehicles and the energy prices, where the last could differ if a carbon tax is included. While, the non-energy costs (*NonEnergyCost*) takes into account the costs related to vehicle maintenance and purchase. Lastly, these components are related to the vehicle passenger load, which eventually translates into a cost per passenger kilometre in USD per region (*r*), per vehicle (*v*) over time (*t*)

The energy costs (*EnergyCosts*) are calculated as follows:

$$EnergyCosts_{v,t} = NetPresentValue_{r,t} * Efficiency_{r,fl,v} * EnergyPrice_{r,fl,v} \left[\frac{USD}{vkm}\right] \tag{4}$$

Where the indices stand for different regions (*r*), fuels, (*fl*), vehicles (*v*) and time (*t*). Furthermore, the net precent value (*NetPresentValue*) takes into consideration the expected lifetime of the vehicles and its resulting costs to certify for depreciation. This is calculated as follows:

$$NetPresentValue_{r,t} = \frac{\left(1 + DiscRate_{m,r,t}\right)^{lifetime} - 1}{\left(1 + DiscRate_{m,r,t}\right)^{lifetime} * DiscRate_{m,r,t}} [-] \tag{5}$$

Where lifetime represents the period in which the vehicle can be used, and the discount rate is used to decrease the present value of energy costs in the future.

Lastly, the inertia of the system, which influence and diminish the influence of energy prices on the fleet share or the mode split, is taken into account. Here, it is assumed that the inertia of the system is caused by the lifetime of certain technologies. This is done, with a simple vintage formulation, that only introduces a new technology on the market after the old technology is expired. This relationship is described in Equation 4:

$$\frac{da_m}{dt} = \alpha * (a\_old_m - a\_optimal_m) \ [-] \tag{6}$$

Where α is the inertia factor based on the lifetime of the technology. *A_old* describes the modal share of the previous time step and *a_optimal* presents the share based on income and accumulated prices. For the aircrafts in the model, a lifetime of 25 years is assumed (Girod et al., 2012).

2.4 The aviation sector

Air transportation is a modern way to transport humans and goods across the globe, which has increased immensely in activity levels over the last decades. To reduce the sectors impact on GHG emissions, technological and design improvements have been implemented over the years. However, the impact of these change are minimal, due to the large increase in air travel demand. The total number of global passengers increased from 100 million in 1960 to an astonishing 4.5 billion in 2019 (Hasan et al., 2021). The air transportation of goods and humans are recognized to have an important relationship to economic growth. For example, it is estimated that the aviation sector in 2019 contribute 619.3 billion US$ to the global GDP (ATAG, 2020). However, the sector is also closely linked to the increase of global GHG emissions. For instance, the global aviation sector in 2019 was responsible for releasing 915 Mt CO^2 in the atmosphere, which was 12% of the global transport CO^2 emissions, and 2% of global induced emissions by humanity (ATAG, 2020). Furthermore, the top five countries (USA, China, United Kingdom, Germany and Japan) were responsible in 2019 for 40% of the total GHG emissions resulting from aviation bunkers (Graver, Brandon et al., 2020). Additionally, other regions are also picking up speed. In the past 20 years, an intense growth in activity levels of 13% per annum, measured in passenger kilometre, is observed in the middle east. While for Asia-Pacific, North America and Europe, an annual growth rate of 8.8%, 5.7% and 5%, respectively, is noticed (Hasan et al., 2021).

Clearly, the COVID-19 pandemic has an immense impact on the aviation sector as a whole. In 2020, an overall reduction of 74% of international passenger is observed, while the domestic aviation traffic is reduced with 50% (ICAO, 2020). Nevertheless, given the sectors close relationship with the global economy, it is expected that the activity levels bounces back to their original pathway, once the restrictions due to the pandemic are withdrawn. For cross continental long haul travel purposes, there are simply no alternative transport modes, which can compete with the speed of aviation transport. While, High-speed train (HST) might offer an alternative for the replacement of short haul air travel, but only on locations where the required rail infrastructure exists.

The aviation sector is not only characterized by a high growth rate in demand in comparison with other transport modes, but the sector also lacks easy implementable technological solutions for the mitigation of GHG emissions, which make the sector specifically hard-to-abate. Currently, the sector is mostly dependent on carbon intensive petroleum fuels. However, continued scientific research shows several solutions to decrease the carbon intensity of the sector (Hasan et al., 2021): 1) Switch from carbon intensive fuels, such as kerosene, to drop-in sustainable aviation fuels, such as bio-fuels or Power-to-Liquids. These fuels require no modifications on ground refilling existing infrastructure, aircrafts engines or the aircrafts themselves, which make them particularly suitable to reduce GHG emissions. 2) Improve the efficiency of the aviation fleet by enhancing the aircraft designs, such as improved fuel efficiency, retrofitting, and weight reduction of aircrafts. To illustrate this potential, Dahlmann et al. (2016), argued that a replacement of the A330-200 fleet with redesigned improved aircrafts could contribute to a GHG reduction potential of 32%. 3) Introduction of alternative propulsion technologies, such as all-electric aircrafts or hydrogen fuelled aircrafts. However, the potential of these aircrafts is limited to short distance trips, due to the limited volumetric energy density in relation with the mass energy density of the energy used in these airplanes in comparison with jet-fuel kerosine. 4) Alternative transport modes for short travel, such as a modal shift to high-speed train.

An additional challenge for developing emission mitigation policies, is caused due to international character of the aviation sector. For example, the sector is currently not part of the Paris Agreement or the European trading system (Hasan et al., 2021). Furthermore, while the emissions of domestic aircrafts are placed under the Nationally Determined Contributions, which makes countries responsible for those emissions, the international emissions from aviation are not. Consequently, this results in a non-level playing field of the sector. In 2016, the ICAO introduced the first market-based mechanism to achieve a low carbon growth of the international aviation sector by 2020, called the Carbon Ofssetting and Reduction Scheme for International Aviation (CORSIA). However, the implementation phase of CORSIA (2021 – 2026) is considered to be voluntary by the participating member states (Strouhal, 2020). Furthermore, binding mitigation measures are not part of CORSIA, since the members states prefer aspirational targets instead. These examples shows the hurdles, challenges and opportunities of the aviation sector to reduce its global GHG emissions. It becomes clear that a sustainable growth of the sector is difficult to achieve. Therefore, it is absolutely necessary to attain a deeper understanding how climate change mitigation pathways could potentially help to decarbonise the aviation sector.

3. Methods

In this section, a schematic overview of the research methodology is presented. Furthermore, a deeper explanation is given on the research methods applied to answer the sub-questions. Moreover, the type and sources of data collected in this study are further clarified.

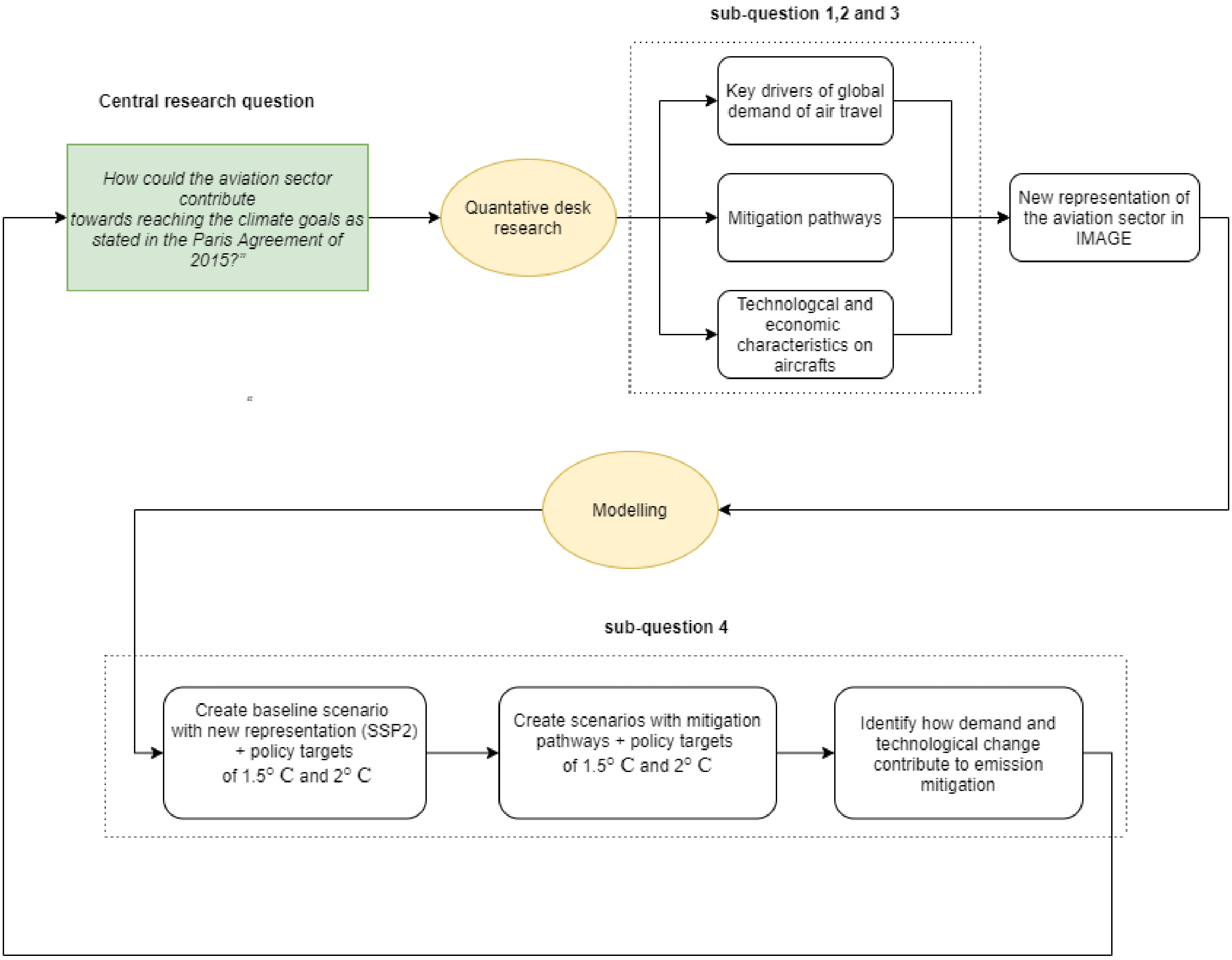

Figure 4: A visualisation of the research methodology

Demand of air travel

The aviation sector is characterized by a strong historical growth in activity. Furthermore, it is expected that the demand of air travel will continue to rise in the coming decades. To comprehend the conflict between climate change mitigation and air travel, a profound understanding is required on the key drivers of air travel demand. For that reason, a thorough quantitative desk research is conducted in scientific literature on this matter. This insight helps to understand why the demand of air travel is expanding, and which key drivers are responsible for this growth.

Mitigation pathways

Due to the growth of activity in the aviation sector, while lacking cost-effective reductional technologies or barriers implementing these, GHG emissions are expected to rise sincerely. In order to understand how technological change and demand in the sector contribute to emissions mitigation, it is required to analyze the most important mitigation pathways reviewed in literature. This knowledge will help in understanding the relation between emissions and possible mitigation pathways, which is necessary to develop and model the mitigation scenarios conducted in this study. The crucial mitigation pathways are reviewed by means of conducting a quantitative desk research in scientific literature. Furthermore, in IMAGE, the transport sector is characterized in two main categories, namely passenger travel and freight transport. The distribution of fuel use of the aviation sector in 2018 can be divided in 81% for passenger travel, and merely 19% for freight transport (Gössling & Humpe, 2020). Since, fuel use in todays aviation sector, is directly linked to GHG emissions, such an distribution could be expected for CO_2 emissions for both sectors. However, due to time constrains, this study is solely focussed on mitigation pathways regarding passenger travel in the global aviation sector. Nevertheless, the emissions of freight travel are also taking into account, since this sector is embedded in IMAGE.

Technology development of aircrafts

To comprehend how technological change in the aviation sector relates to GHG emissions, different types of aircrafts operated in the aviation sector over the years are described in IMAGE. In this description, information about the year of introduction on the global market, the energy efficiency, the fuel type and the investment costs of these aircrafts are provided. However, since technological change tends to occur rapidly in this sector, a new representation of different types of aircrafts utilized in the model is necessary. To illustrate this, due to the rapid development in battery technology, an all-electric aircraft becomes more realistic in the future, than was previously thought (Schäfer et al., 2019). For that reason, the technology and economic characteristics of historical, current and future aircrafts, are explored by conducting desk research in scientific literature and online documentation or reports presented by the International Energy Agency (IEA) and associations of the aviation industry, such as the International Air Transport Association (IATA), the International Civil Aviation Organization (ICAO), or by documents provided by the aircraft manufacturers Boeing or Airbus. This research results in a new representation of the aviation sector in IAMGE. This overview contains information about the different types of aircraft utilized in the aviation sector, based on the fuel efficiency, investment costs, types of fuel used, and the year in which the aircraft is introduced on the global market. Furthermore, the potential trip distances of the airplanes are also taken into account, since some type of aircrafts, such as hydrogen fuelled aircraft, have limited trip distances. This is done by gathering and analysing data from University College London, whom modelled the revenue passenger kilometre of global air flights over the years, while making a distinction between short- medium- and long distance trips.

Modelling mitigation scenarios

When the key drivers of global demand of air travel, the most important mitigation pathways and the technological developments of the aviation sector are identified, the question arises how the demand and technological change contribute towards to emissions mitigation. This dilemma is explored with the conduction of model execution in IMAGE in combination with scenario analysis. First, a baseline scenario is developed based on SSP2, as described in 2.1.1 Shared Socioeconomic Pathways, in which the new representation of the aviation sector is applied. After this, several mitigation pathways are developed, and compared to the baseline scenario in terms of emissions, travel demand, energy use, the composition of the fleet, and the fuel mix used by the sector. Subsequently, a policy target is included in the model, by introducing a profound carbon tax obtained from the FAIR model. First, another SSP2 scenario is developed, but with the constraint that the 2° C target is met. Secondly, the policy target of 1.5° C is introduced in the model. These targets are chosen since they form the basis of the climate goals stated in the Paris Agreement (UNFCCC, 2015). Both scenarios are again used as the baseline scenarios, while the mitigation pathways scenarios are also executed again, thus this time with a profound carbon tax included to reach the stated climate targets. Hereafter, these scenarios are compared with one another and described how emissions, travel demand, energy use, the composition of the aviation fleet, and the fuel mix differ. With this information an answer is given on how the aviation sector could contribute towards reaching the climate goals as stated in the Paris Agreement of 2015.

4. Results

In this section, the results of the sub-questions are presented. First, the key drivers of global air travel demand are identified. Secondly, an overview is given of the most important mitigation pathways, which will be included in the developed mitigation scenarios. Thirdly, a summary of the categories of aircrafts used in IMAGE is presented. Lastly, the climate mitigation scenarios, regarding the aviation sector, are introduced and discussed.

4.1 Key drivers of air travel demand

Air transportation has a long-term relationship with economic growth, and over the last few decades the aviation sector has undergone an intense growth in activity (Nasreen et al., 2018). While technology and design improvements have been realized to reduce the sectors GHG emissions, the impact of these developments are minor when compared to the large increase of global activity measured in RPK. The total RPK has increased from 109 billion in 1960 to an overwhelming 8,686 billion in 2019, resulting in an annual growth rate of 7.7% (Hasan et al., 2021).

Many studies has been conducted to identify the key drivers of air travel demand. Graham (2000) shows that leisure air travel demand is linked to social and economic conditions, such as leisure time and income, as well as price and quality. In spite of this, Pearce (2008) concludes that tourist are indeed sensitive to price fluctuations on competing airlines, but the overall market is not. The main key drivers of air travel demand that he identified were economic growth and income. This finding is in line with a study by Gallet & Doucouliagos (2014), who conducted a systemic review on the income elasticity of air travel. They concluded that the income elasticity of domestic routes is 1.186, while for international routes this is 1.546. This implies that both markets have not reached maturity or saturation so far, and the demand for international flights is more volatile to changes in income than for domestic flights. However, Becken & Carmignani (2020) concluded that demand for air travel is mostly driven by income approximated through Gross Domesic Product (GDP), and the price of an airfare. Furthermore, they questioned the predicted annual growth trajectory of 4.7% and 4.4% from Boeing and Airbus respectively, by showing how climate change as a crucial aspect could seriously effect both key drivers. Nevertheless, an overall consensus emerges that travel air demand is mostly driven by income resulting from GDP in combination with population growth. These drivers are also marked as key drivers in IMAGE.

4.2 Mitigation pathways of air travel emissions

In this section, different possible mitigation pathways reviewed in the literature are addressed. Furthermore, the scenario's utilized in this study to explore the most important mitigation routes are demonstrated and discussed.

4.2.1 Sustainable aviation fuels.

In a study by Hasan et al. (2021) a list of different emission mitigation pathways are examined to identify possible solutions to reduce the GHG emissions of the aviation sector. An important pathway is to use sustainable aviation fuels (SAF) instead of kerosine type jet fuels in aircrafts. Several studies have shown the potentials of SAF, such as biofuels, as a renewable drop-in alternative to jet fuels (Bauen et al., 2020; Tanzil et al., 2021). Biofuels are produced from biogenic feedstocks (i.e. sugar, starch crops or vegetable oils) or from renewable hydrogen and CO_2. These biofuels are functionally identical to fossil jet kerosine, and could therefore be used in today's existing aircrafts without major modifications on infrastructure or the engine of the plane (Tanzil et al., 2021). Hasan et al. (2021) showed that an increase of biofuels in the aviation energy mix to 11.4% by 2050 could contribute to achieve 11% of the 2050 emissions reduction target stated in the study. However, the costs of these alternative fuels are considerably higher (two to five times) in contrast to kerosine jet fuel. Furthermore, the sustainability impact with regard to land use change, in the case of biofuels based on energy crops, is also important to consider. In a study by (Bauen et al., 2020) it is estimated that GHG emissions can be reduced by 65% with the use of conventional crops based routes, and 95%, when renewable energy routes are used.

4.2.2 Alternative propulsion technologies

Another essential mitigation pathway, is the introduction of alternative propulsion technologies on the aviation market, such as all-electric aircrafts or hydrogen-fuelled aircrafts. The advantage of these technologies is the reduced impact on climate change in comparison with the current kerosine fuelled aircraft. All-electric airplanes have the potential to eliminate direct CO_2 and non CO_2 emissions (Schäfer et al., 2019), while hydrogen-fuelled aircrafts, powered by H_2 combustion or a fuel cell, does not generate any direct CO_2 emissions at the point of use (Petrescu et al., 2020). However, fuel cell based or direct hydrogen-combustion engines emits two and a half times more water vapor in the air in comparison to kerosine combustion. The potential climate impact of this is still inadequately understood, and more research is needed in this area (McKinsey & Company, 2020). Nevertheless, a reduction potential of 50 – 90% compared to kerosine powered aviation seems feasible, according to the authors.

A disadvantage of these technologies is the dependency on trip distances. Due to the low specific energy of todays best lithium-ion batteries (250 Wh kg^{-1}) in combination with a low energy to weight ratio, the all-electric aircraft is limited to short-distance trips. Schäfer et al. (2019), shows that a specific energy of the battery-pack of 800 Wh kg^{-1} is needed, to cover a distance of 1.111 km, which is assumed to be feasible around mid-century. If this specific energy is reached, all-electric aircrafts could substitute up to half of the global-departures, and 15% of the global RPK (Schäfer et al., 2019). The same dependency on trip distances holds for aviation fuelled aircrafts. It is estimated that H_2 aircrafts, powered by a fuel cell, is only feasible to the short-range segment (165 PAX, 1500 km) while an aircraft with a H_2 combustion turbine could be applicable in the medium-range section (250 PAX, 7000 km) (Jonas Kristiansen Nøland, 2020).

4.2.3 Reduce air travel demand

To reduce air travel demand, the option to switch short-distance passenger air travel towards High-Speed Train (HST) is considered as another feasible mitigation pathway to reduce GHG emissions (Hasan et al., 2021). However, as the literature indicates, a growth of income normally leads to an effect in which a modal shift from land-based or sea-based modes of transport to aviation is observed, instead the other way around (Scholl et al., 1996). Nonetheless, a study by Prussi & Lonza (2018) shows that a modal shift from aviation to high speed train (HST) in Europe could reduce GHG emissions in a range from 4% to 21.6%. Furthermore, if the speed of HST would increase, a further modal shift from aviation to HST is expected, which could then result in a greater reduction of CO_2 emissions (Yu et al., 2021). Nevertheless, the question arises to what extent this modal shift to high speed train could reduce GHG emissions in the aviation sector.

4.2.3 Improve efficiency of aviation fleet

Non-engine based efficiency improvement, such as lighter components used in aircrafts, and improved fuel efficiency, are considered measures to have a significant impact on the reduction of GHG emissions in the aviation industry (Hasan et al., 2021). These efficiencies reductions pathways consist of the introduction of more fuel-efficient aircrafts on the market, re-engineering of aircrafts, improved air traffic management and technically improved flight patterns (Keramidas et al., 2018). The ICAO has set an aspirational target of 2% per year of improved fleet efficiency between 2021 and 2050. However, the realisation of this goal has been questioned, and an improvement of 1.37% per annum is considered to be more accurate (Gregg G. Fleming & Lépinay, 2019). Hasan et al. (2021) shows that a reduction of 6.3% of GHG emissions is possible in 2050, if an improved fleet efficiency of 1.5% per year is expected. However, in this particular study, the assumption is made that there will be no rebound effect, thus that increased fuel efficiency will not lead to a reduction of ticket prices with travel demand thus remaining stable.

4.3 Technology development of aircrafts

To understand how the aviation sector could contribute towards reaching the climate goals as stated in the Paris Agreement, a thorough analysis of recent developments in technology innovation is required. First, an overview is presented of the current representation of airplanes utilized in IMAGE, in which the technology developments of the aviation sector are described. This is done by defining a specific aircraft as a vehicle description, while taking into account the fuel used by the aircraft, the year in which the technology is introduced on the market, the energy efficiency and the investment costs. Secondly, the new representation of aircrafts in IMAGE is shown and further discussed.

4.3.1 Current representation of aircrafts in IMAGE

The current representation of aeroplane types applied in the IMAGE model is based on several studies found in literature and shown in **Fout! Verwijzingsbron niet gevonden.**.

Table 1

Aeroplane types, fuel use, year of introduction, energy efficiency and additional costs (Girod et al., 2012)

Vehicle description	Fuel type	Year of introduction	Energy efficiency (MJ/pkm)	Additional costs [cents (2005 USD)/pkm]
Air, before 1980	Oil	-	3.5	0
Air, 1980	Oil	1980	3.0	0.29
Air, 2000	Oil	2000	2.0	1.18
Air, 2000	Bio	2015	2.0	1.18
Air, improved eff.	Oil	2020	1.5	1.93
Air, improved eff.	Bio	2020	1.5	1.93
BWB	Oil	2040	1.0	3.20
BWB	Bio	2040	1.0	3.20
BWB, improved eff.	Oil	2050	0.8	4.02
BWB, improved eff.	Bio	2050	0.8	4.02
Cryoplane	H_2	2050	1.6	6.49

Note: US (2005) load factor is assumed for efficiency and costs.
Abbreviation: BWB: Blended Wing Body. Cryoplane: H_2 fuelled aircraft. Eff: efficiency.

The energy efficiencies of various aircrafts (Air, before 1980; Air, 1980; Air, 2000) are based on a study by Lee et al. (2001), in which the historical fuel efficiency of the global air transport fleet is examined. The efficiency of the "improved efficiency" variants are derived from the IEA Bluemap scenario (IEA, 2009). A new radical concept of an improved design of future airplanes is called the blended wing body, and in the model its efficiency is based on projections by Schäfer et al. (2010). Furthermore, the efficiency of the cryoplane are rough estimates based on the studies by Krijnen and Astaburuaga (2002) and Westenberger (2008). Finally, the additional costs of every category are derived from the technology-cost relationship for aircrafts suggested by Lee et al. (2001), which is further explained in the next paragraph.

4.3.2 New representation of aircrafts in IMAGE.

Here, the new representation of aeroplane types utilized in the IMAGE model is presented. The specifics of each technology are based on studies found in literature as described in the following section, and visualized in Table 2.

Table 2

Aeroplane types, fuel use, year of introduction, energy efficiency and additional costs

Vehicle description	Fuel type	Year of introduction	Energy efficiency (MJ/pkm)	Additional costs [cents (2005 USD)/pkm]
Air, before 1980	Oil	-	3.5	0
Air, 1980	Oil	1980	3.0	0.28
Air, 2000	Oil	2000	2.0	1.12
Air, 2000	Bio	2015	2.0	1.12
Air, 2015	Oil	2015	1.34	2.08
Air, 2015	Bio	2015	1.34	2.08
Air, next generation	Oil	2019	1.15	2.60
Air, next generation	Bio	2019	1.15	2.60
Air, subsequent generation	Oil	2039	0.99	2.98
Air, subsequent generation	Bio	2039	0.99	2.98
BWB	Oil	2040	0.96	3.18
BWB	Bio	2040	0.96	3.18
BWB, improved eff.	Oil	2050	0.87	3.53
BWB, improved eff.	Bio	2050	0.87	3.53
All-electric	*Electricity*	*2040*	*0.65*	*4.71*
Cryoplane	*H_2*	*2040*	*0.99*	*4.67*

Note: US (2005) load factor is assumed for efficiency and costs.
Abbreviation: BWB: Blended Wing Body. Cryoplane: H_2 fuelled aircraft. Eff: efficiency.

Vehicle description, fuel type, year of introduction and energy efficiency of chosen technologies

For the first four aviation categories, the data regarding the vehicle description, fuel type, year of introduction, the energy efficiency and additional costs, is based on historical data derived from Lee et al. (2001) as previously described. For that reason, these categories remain unchanged. However, as noticeable, the additional costs are revised, since minor flaws were noticed in the model, like an incorrect conversion from 1995 US$ to 2005 US$ in the calculations.

The data for the next ten aviation categories (Air; 2015, next generation, subsequent generation and blended wing body) is derived from a study by Dray et al. (2018). This study conducts a thorough analysis of the benefits and costs of new technologies used in the aviation sector to show how the uptake of these technologies could reduce the carbon intensity of the sector. Its data analysis is performed with the usage of AIM 2015: an open-source aviation systems model, which has shown to be valuable for creating emission mitigation scenario's (Dray et al., 2019).

Importantly, in the paper by Dray et al. (2018), hybrid or battery electric and cryoplanes are excluded as they are considered to be more speculative by the authors. This is in contrast to several recent publications concerning these technologies. For instance, IATA published its "Aircraft Technology Roadmap to 2050" report, in which all electric powered planes and cryoplanes do play a significant role. Furthermore, a fact-based study by McKinsey & Company (2020) shows the importance, potential, limitations and feasibility of hydrogen powered airplanes, while a report by Boeing discusses the opportunities for hydrogen in commercial aviation (Bruce et al., 2020). These reports are further backed up by scientific literature, such as the study from Schäfer et al. (2019) in which the technological, economic and environmental prospects of all-electric aircrafts are discussed. Moreover, a study by Jonas Kristiansen Nøland (2020) shows the potential of hydrogen fuelled aircrafts as well as the approximated years of this technology to enter the market. Notably, a research from Verstraete (2015), shows how the energy efficiency of hydrogen-fuelled aircrafts varies with range, and how this limits the potential of this technology for long-distance trips.

Given the considerable amount of literature supporting all-electric aircrafts and cryoplanes, both of these technologies are included in IMAGE. However, as the literature reveals that both technologies have their limits regarding trip distances, it is assumed that all-electric aircrafts can only be used for short distance trips (< 926 km), while cryoplanes are only applicable for medium- and short distance trips (<1481 km) (Bruce et al., 2020; Schäfer et al., 2019).

Additional costs

The additional costs of the different technologies are based on the technology-cost relationship as proposed by Lee et al. (2001). In this study, a mathematical relationship is found between direct operating cost (DOC) of an aircraft and its fuel efficiency. This calculation is shown in Equation 7.

$$\ln\left(\frac{DOC}{RPK}\right) = -0.958\ln(\eta) + 3.83 \tag{7}$$

Where DOC/RPK is the direct operating cost divided by the revenue passenger kilometre in cents 1995 US$ and η is the fuel efficiency in RPK/ kg fuel. Furthermore, Lee et al. (2001) defined a relationship between the paid price of an airplane and the DOC/RPK. This correlation is presented in Equation 8.

$$\ln\left(\frac{Price}{Seat}\right) = -0.545\ln\left(\frac{DOC}{RPK}\right) + 6.06 \tag{8}$$

Where Price/Seat is the aircraft price per seat in 1995 thousand US$ and DOC/RPK is the direct operating cost divided by the revenue passenger kilometre in cents 1995 US$. Moreover, in Figure 3.10 of this research, a typical DOC + investment cost composition of aircrafts is displayed. Here, it is indicated that 60.5% of the price is composed from DOC, while 39.5% is related to the investment cost. Finally, with this information, the investment cost in cents US$ 2005 per passenger kilometre (PKM) is calculated for each different technology. The Air, before 1980 category is used as a baseline, and therefore has an additional cost of 0, while the other technologies has additional costs (investment costs) in comparison with the baseline technology. Furthermore, the additional costs of cryoplanes are corrected, because of the lower vehicle load due to the large hydrogen tank required which would result in volume lost.

4.4 Modelling mitigation scenarios

The climate change mitigation scenarios performed in this study are presented and discussed. First, an overview is given on the different scenario utilized in this study. Secondly, an explanation is given on how the modelling is executed. Lastly, the results derived from the scenarios are provided.

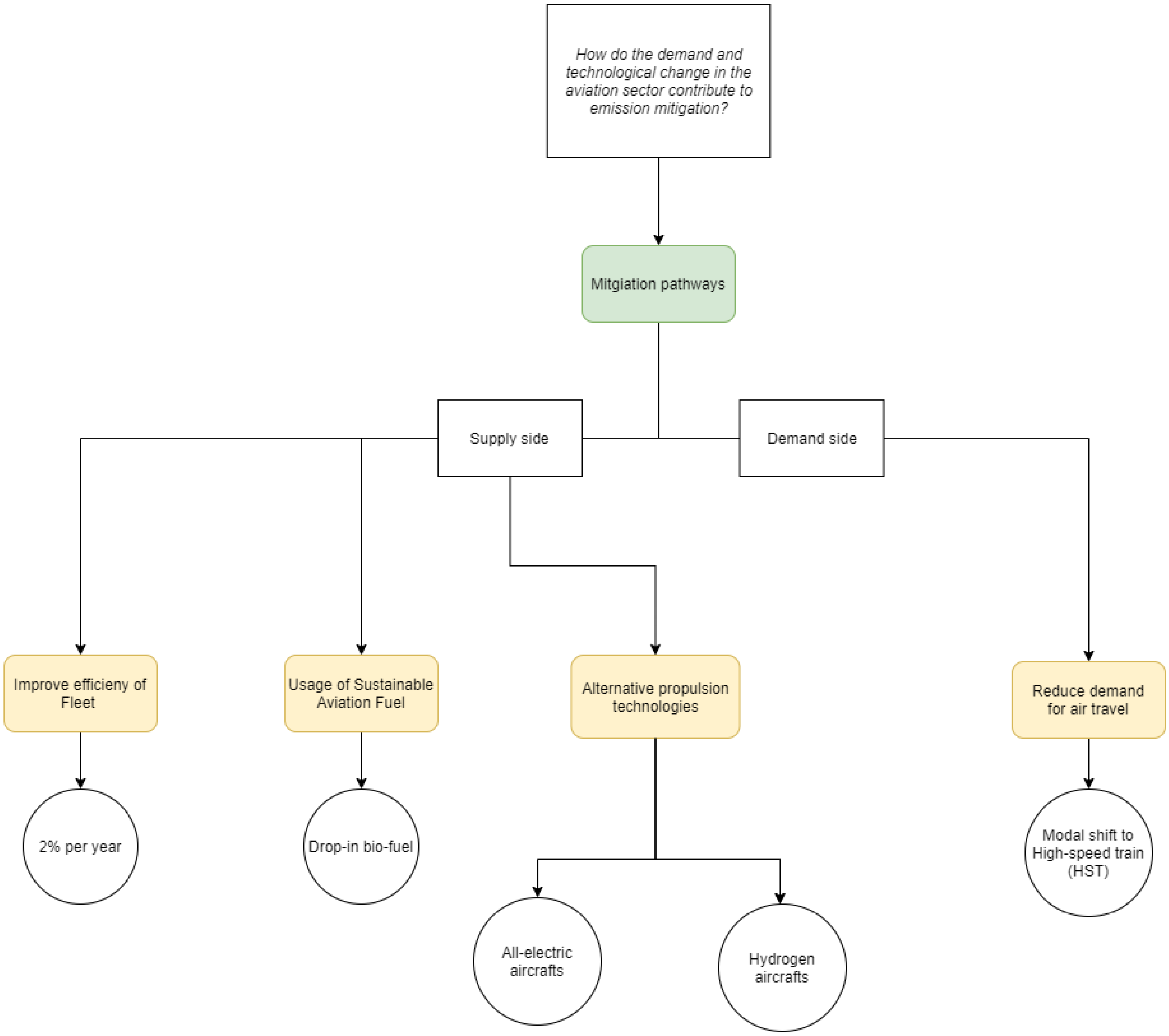

Figure 5: A schematic overview of the four mitigation pathways conducted in this study.

4.4.1 Overview of scenarios

In this study, four different mitigation pathways are constructed, and compared to a baseline scenario in terms of emissions, travel demand, energy use, the composition of the fleet, and the fuel mix used by the aviation sector. Hereafter, the same scenarios are executed again, but with a policy target of 1.5° C and 2° C included. A schematic overview of the mitigation pathways is shown in Figure 5, while in Figure 6 an outline is given to clarify the structure of the developed scenarios.

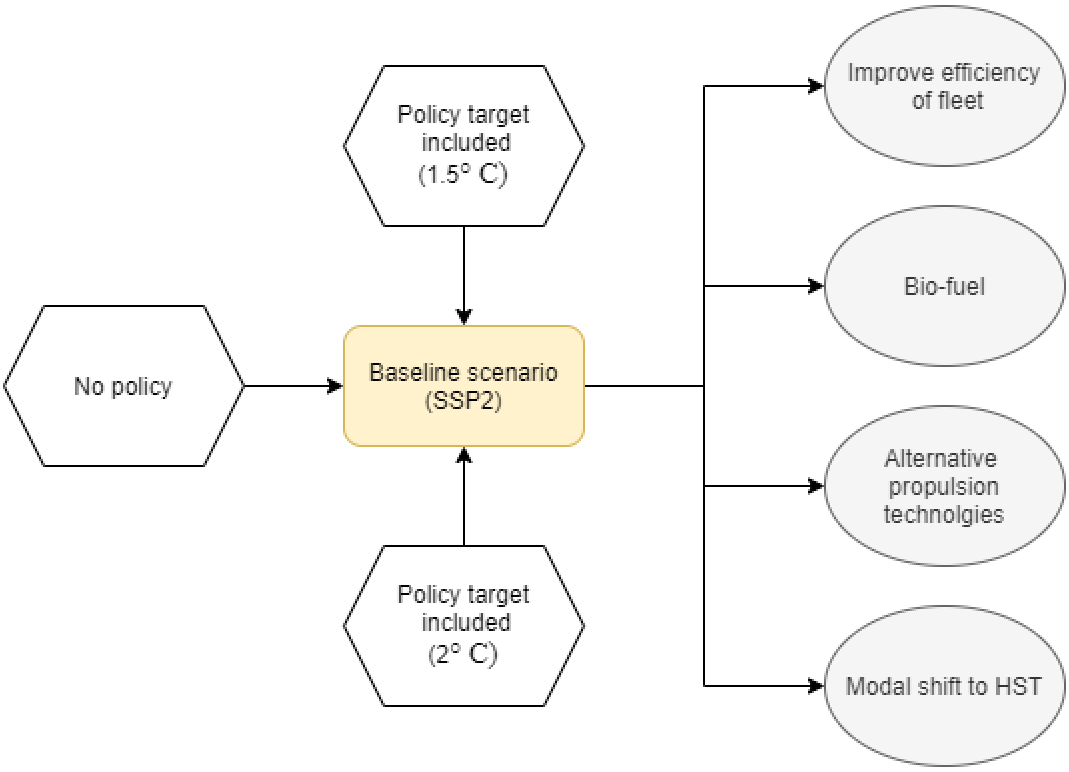

Figure 6: The structure of the developed scenarios

Baseline scenario

The new representation of the aircraft technologies, described in Table 2, are used as input for the baseline scenario, to which the mitigation pathways are compared to. Furthermore, the scenario is based on SSP2, described in paragraph 2.1.1. Shared Socioeconomic Pathways. The All-electric and hydrogen aircrafts are excluded, because they form the basis for the alternative propulsion scenario.

Improve efficiency of fleet scenario

As stated in paragraph 4.2.3 Improve efficiency of aviation fleet, the ICAO has set a target of 2% improved efficiency of the global aviation fleet from 2021 to 2050 by improving fuel efficiency and non-engine based efficiency enhancements. To understand how this target influences the reduction on GHG emissions in the sector, the following assumptions has been made: the aircraft, next generation introduced in 2019 and the BWB introduced in 2040 are marked as the baseline fuel efficiency aircrafts. Consequently, the aircraft, subsequent generation introduced in 2039 and the BWB, improved efficiency introduced in 2050, have an improved efficiency improvement of 2% per annum in comparison with these baseline aircrafts.

Biofuel scenario

As explained in paragraph 2.3.2 Equations and assumptions of TRAVEL, the choice to invest in a certain aircraft technology, like Air 1980 (Oil), is dependent in the model on the monetary cost of CostPerPkm. After this, an MNL type equation is used to determine the choice of the vehicle type, which then results in a fleet composition, while taking into account the caused inertia due to the lifetime of the aircrafts (25 years). However, as the literature shows, biofuel is considered a drop-in alternative to kerosine. This implies that most aircrafts represented in IMAGE, could switch from oil to bio fuel or vice versa, typically based on the cost of the fuel type used, without the necessity for an alternative type of aircraft. Nevertheless, this phenomenon is not captured perfectly in the model, since the fleet composition is purely based on the CostPerPkm at a specific moment in time. If the oil type airplane is preferable at that instant, it can only be utilized as an oil type aircraft during its lifetime. To tackle this problem, another MNL type equation is constructed after the fleet composition is established. In this MNL equation is assumed that the five-year average energy price of bio fuel and oil (tax included) is the deciding factor, to redefine the share of a technology aircraft in the total stock of a region. This is only possible if the aircraft type has a bio fuelled counterpart in the model.

Alternative propulsion technology scenario

As shown in Table 2, all-electric and hydrogen fuelled aircrafts are included in the model to understand how these technologies could contribute to climate change mitigation. However, since these technologies are trip distance dependent a distinction between global flight distances is needed in IMAGE. Data is gathered from University College London (UCL), whom modelled the RPK for short distance (<926 km), medium distance (<1481 km) and long distance (>1481 km) for international and domestic flights for the seven continents. This work is executed with AIM 2015: an open-source aviation systems model, and the data set is also based on SSP2. Consequently, the data set is transposed to fit in IMAGE. Each of the 26 regions, are described with a certain share of short, medium or long distance domestic and international aircraft trips. So, if an alternative propulsion technology is chosen, its share in the fleet composition is corrected, based on the trip distance of RPK flown in that region over time. In Figure 7, the modelled global air travel demand is shown, to illustrate how the division of distance trips is allocated over the years. It becomes clear, that the growth of long-distance trips, measured in activity, is remarkable higher than short- and medium distance flights.

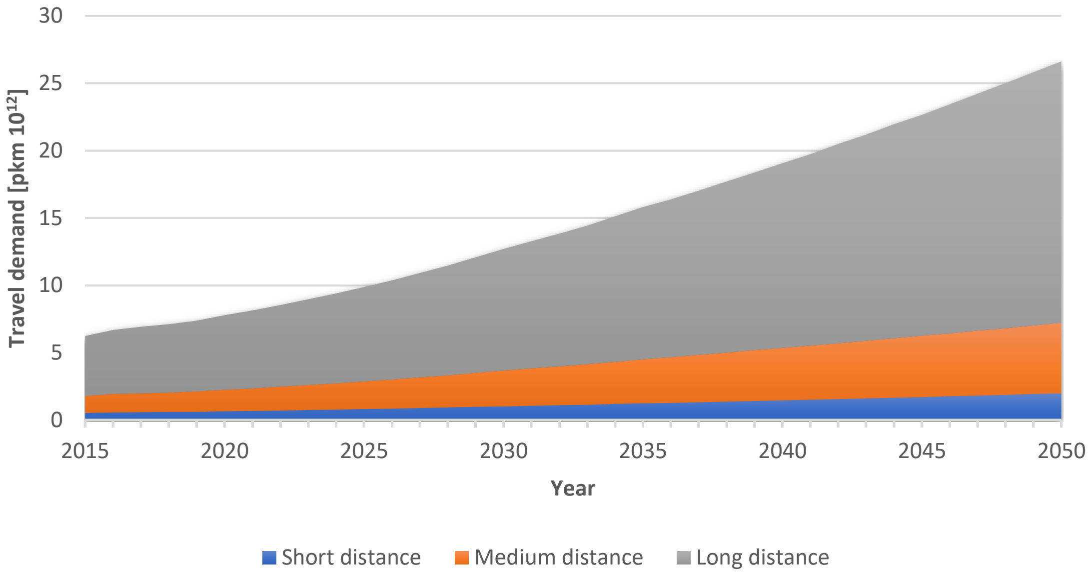

Figure 7: The global travel demand of domestic and international air travel split into short-, medium-, and long distance passenger kilometre.

Modal shift to High-Speed Train scenario

For this scenario, a deeper understanding is required what the impact on climate change mitigation is, if a modal shift from aviation passenger travel to HST occurs. In IMAGE the travel demand of all the different modes is based on several conditions, such as the TTB and TMB constrains, and than fed back into the model. However, for this scenario, after the air travel demand is calculated, a distinction on short distance air travel is made for the 26 regions. This is again based on the data from UCL. Here, it is assumed that the short distance (<926 km) of air travel is taken over by the HST mode from 2022. Furthermore, a smooth transition up to 2030 is assumed. Consequently, the travel demand of these modes is corrected with these assumptions to find the impact on climate change mitigation.

4.4.2 Results of scenarios

In this section the results of the scenarios are provided. First, it is necessary to understand how the emissions of the passenger aviation sector relates to other travel modes in IMAGE. For this, a SSP2 baseline scenario is developed and shown in Figure 8.

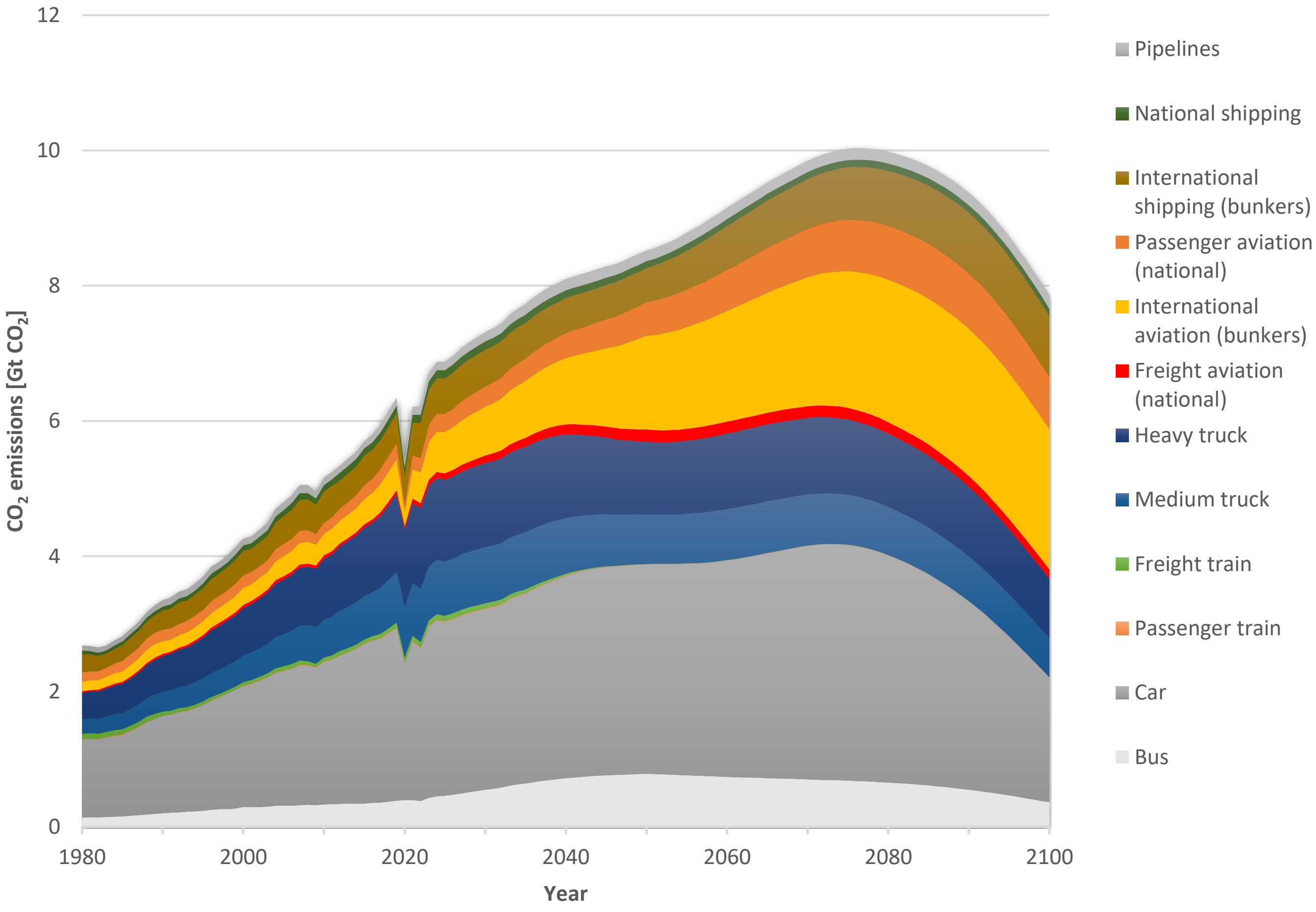

Figure 8: The transport emissions of various transport modes based on a SSP2 scenario run by IMAGE

Here, it becomes clear that the emissions of air travel (i.e. national passenger aviation; national freight aviation; international aviation) are relatively limited in earlier years in comparison to other transport modes, but the growth rate of aviation emissions develops substantially. Interestingly, international aviation (bunkers) shows the most significant growth over the years, which includes passenger travel as freight transport in one category.

Similar results of growth are observed when examining the global demand of air travel, shown in Figure 9, which partially explains the growth of emissions. However, if a closer look is taken on the fuels used in the aviation sector, visualized in Figure 10, it becomes clear that the growth of emissions is generated due to the expansion of oil usage. The overall efficiency for air travel goes down over the years in a SSP2 scenario, but the increase in demand compensates for this effect, which explains the growth of CO_2 emissions by the sector.

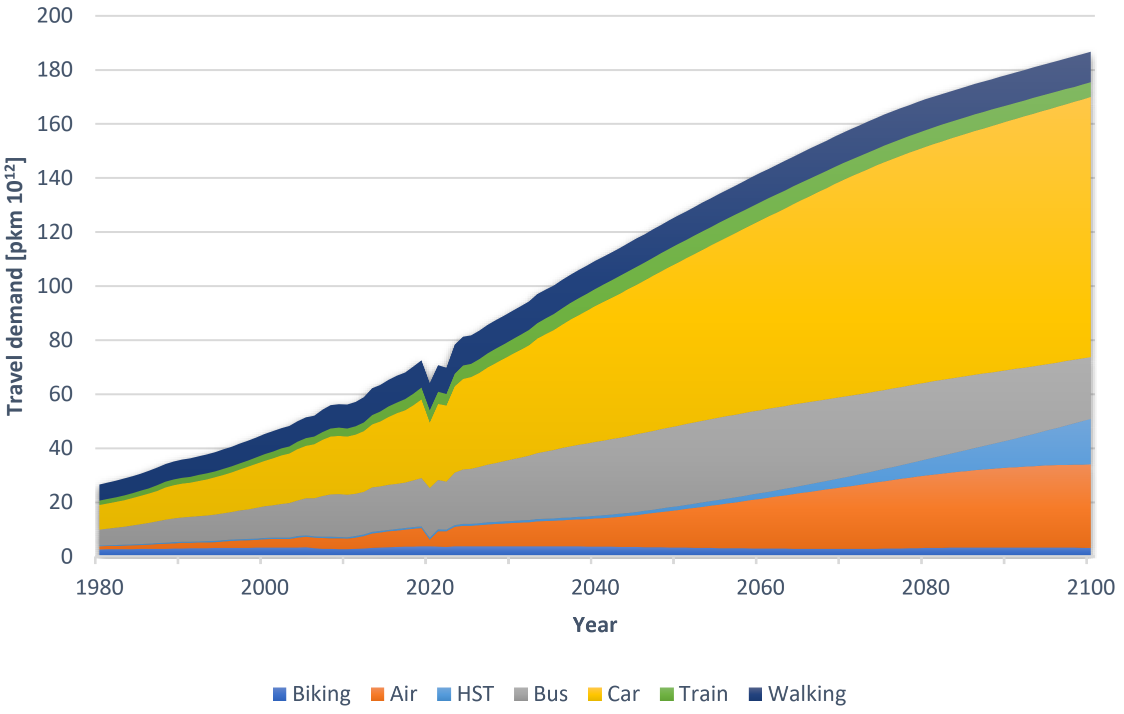

Figure 9: The global travel demand of seven different transport modes (aeroplane, high-speed train, rail, car, foot, bicycle and bus), based on a SSP2 scenario run by IMAGE.

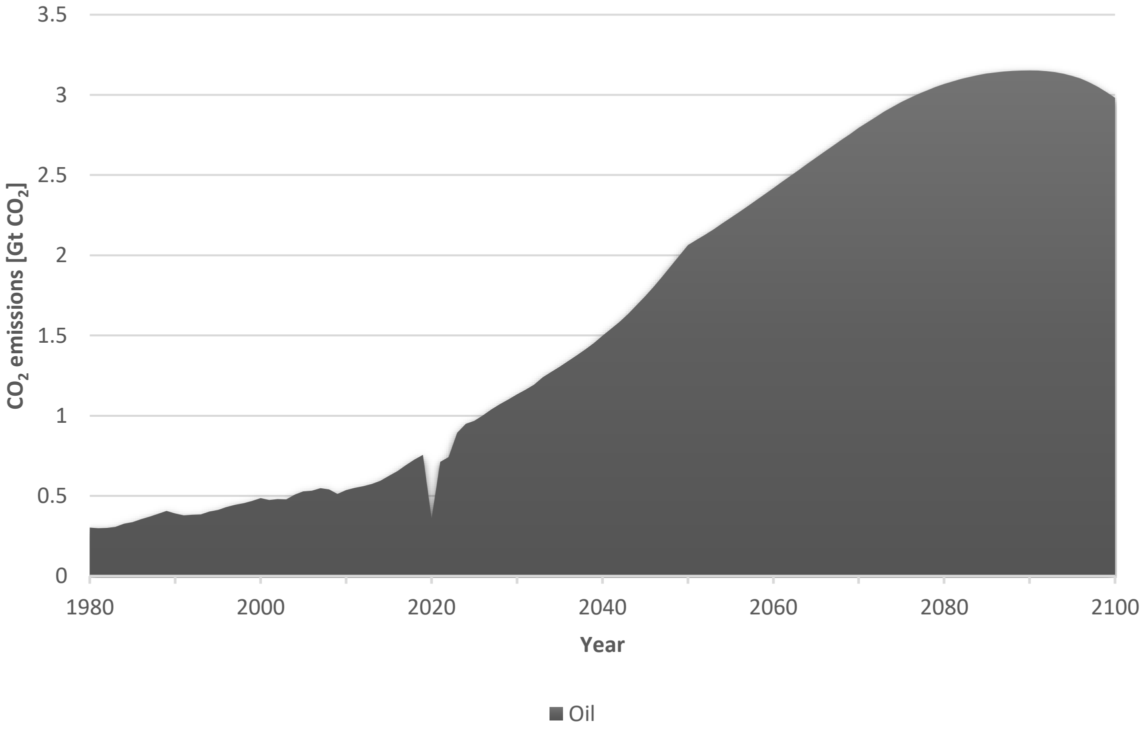

Figure 10: The global CO_2 emissions based on the fuel consumption of domestic and international passenger and freight air travel, developed with a SSP2 scenario run by IMAGE

No policy

The first model is run without any policies included; as will be discussed below, little CO_2 reduction up until the year 2100 is obtained implementing mitigation pathways in this scenario.

Four different mitigation pathways were run in IMAGE (Improved efficiency, Modal shift to HST, Alternative propulsion, and Bio-fuels) and compared to the baseline scenario (SSP2) in terms of CO_2 emissions, passenger air travel demand, energy use, share of fuels, and the fleet composition. As stated, no policy target is included in the model. In **Fout! Verwijzingsbron niet gevonden.** below, it is shown that each mitigation pathway leads to a reduction in global transport emissions of domestic and international passenger air travel and freight, but the quantity differs to some extent. The greatest reduction is achieved with the modal shift to HST (7.3%) and the Bio-fuel (6.8%) scenario. For Improved efficiency and Alternative propulsion, only a reduction of 0.9% and 1.3% is attained, respectively.

In Figure 12, the global travel demand of domestic and international air passenger travel is visualized. The modal shift to HST accomplished the greatest reduction in demand (9.6%), while the change of demand in the bio-fuel scenario is considerably lower (0.23%). Unexpectedly, the alternative propulsion scenario leads to a reduction of 2.8% in passenger air travel demand in comparison with the baseline, as further elaborated upon in the discussion. Notably, the Improved efficiency scenario even shows an increase in demand of 1.3%.

In **Fout! Verwijzingsbron niet gevonden.**, energy use of domestic and international passenger air travel is shown. Here, a reduction of 9.0% is achieved in the modal shift to HST scenario, and the Alternative propulsion reduces its energy use with 2.1%. The Improved efficiency reduces 1.5% of the passenger air travel energy use an the reduction of the bio-fuel scenario is 0.17%, which can be explained by the minor reduction in air travel demand.

In Figure 14, the share of fuel consumption of domestic and international passenger air travel in the year 2020, 2050 and 2100 is depicted. These findings illustrated that the low CO_2 emission reduction obtained could be due to the heavy oil usage of each scenario. The only exception is the Bio-fuel scenario, in which the share of bio-fuel in the energy mix is changed from 5% to 31% in 2100, which explains the rapid drop in CO_2 emissions by the end of this century as seen in Figure 12.

In Figure 15, the fleet composition of the technologies compiled in each scenario in the year 2020, 2050, and 2100 are presented. Here, it shows that each scenario increases their share of more efficient technologies over time, with some minor differences between scenarios. For example, Improved efficiency adopts “Air, 2015 (oil)” more than other scenarios while the most efficient technologies, such as BWB improved efficiency, have not found their way to the global market. Notably, the Alternative propulsion technologies scenarios do not show any electric or hydrogen fuelled aircrafts in the fleet composition, while the Bio-fuel scenario has an increased share of bio airplanes. The fleet compositions of the other scenarios are relatively similar.

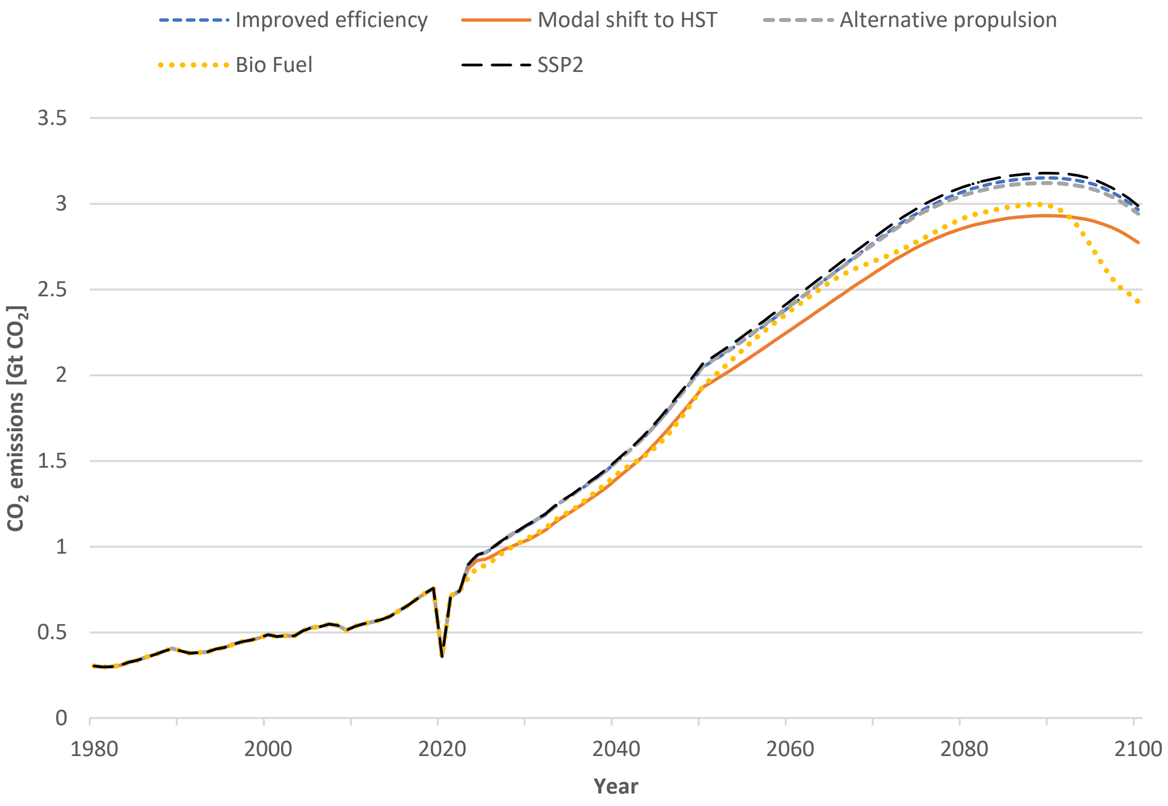

Figure 11: The global transport emissions of domestic and international passenger air travel and freight based on SSP2, in comparison with the emissions from the scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel.

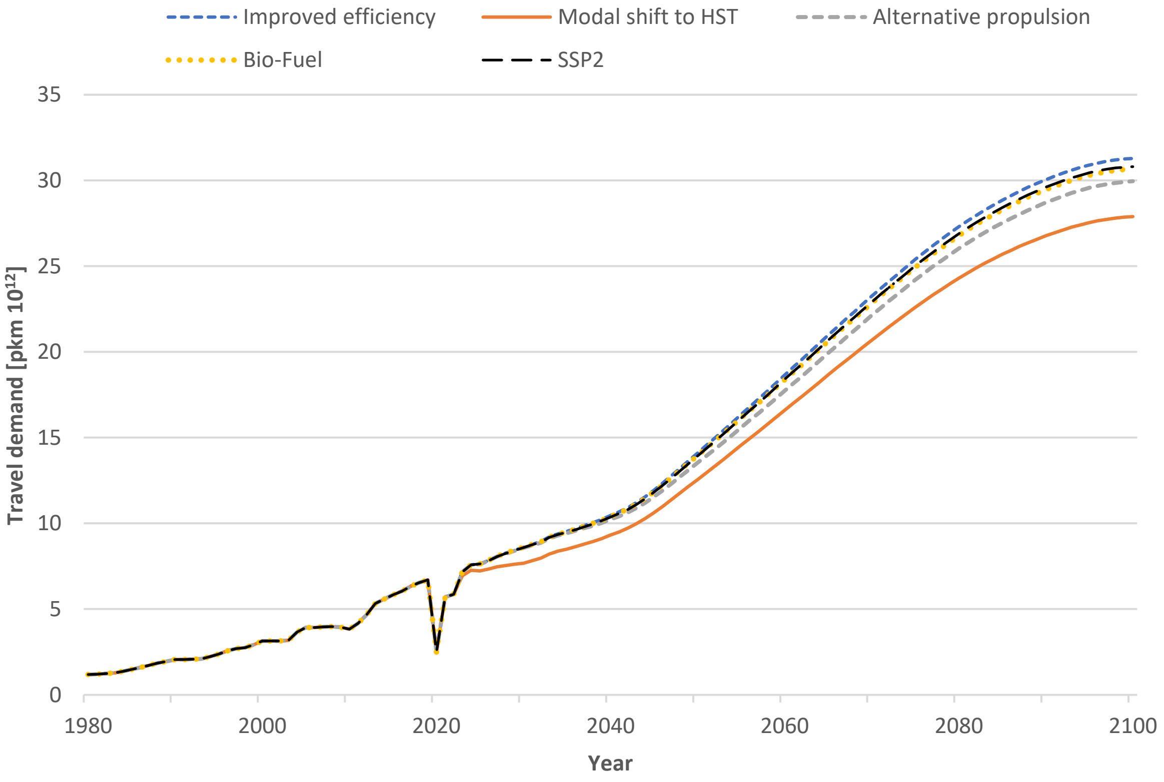

Figure 12: The global travel demand of domestic and international passenger air travel based on SSP2, in comparison with the travel demand from the scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel.

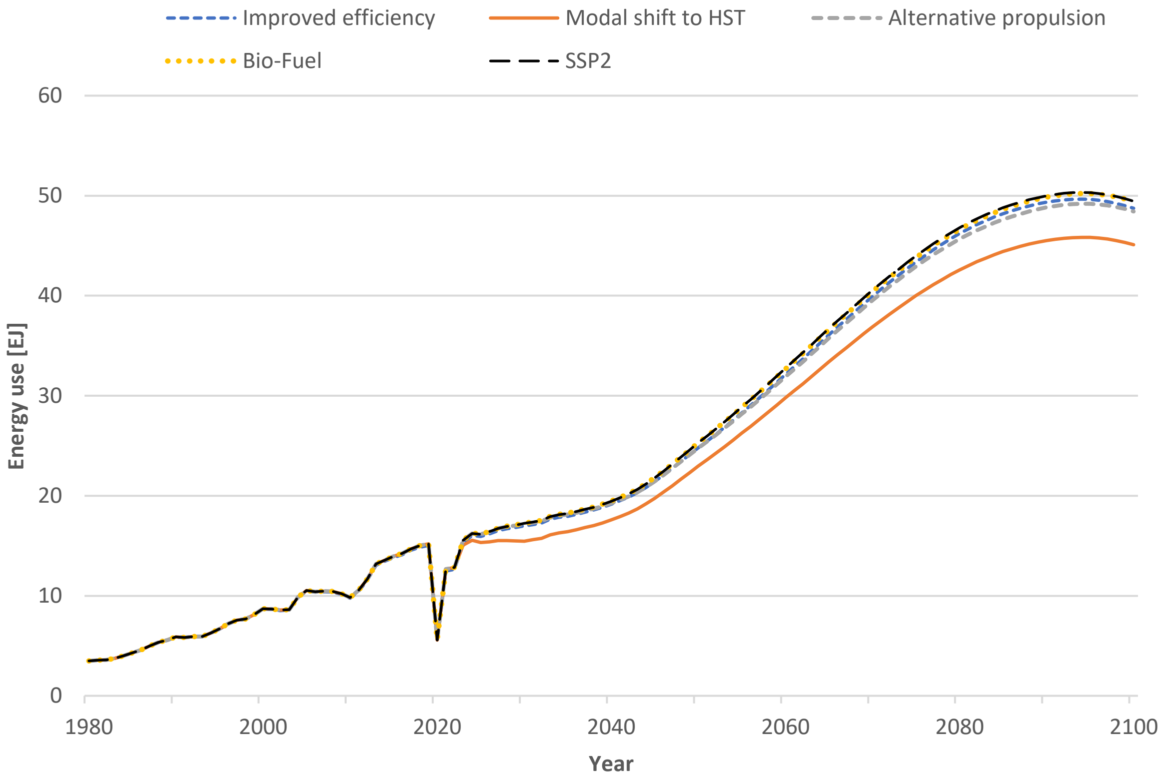

Figure 13: The global energy use of domestic and international passenger air travel based on SSP2, in comparison with the energy use from the scenarios: Improved efficiency, Modal shift to High-speed train, Alternative propulsion, and Bio-fuel.

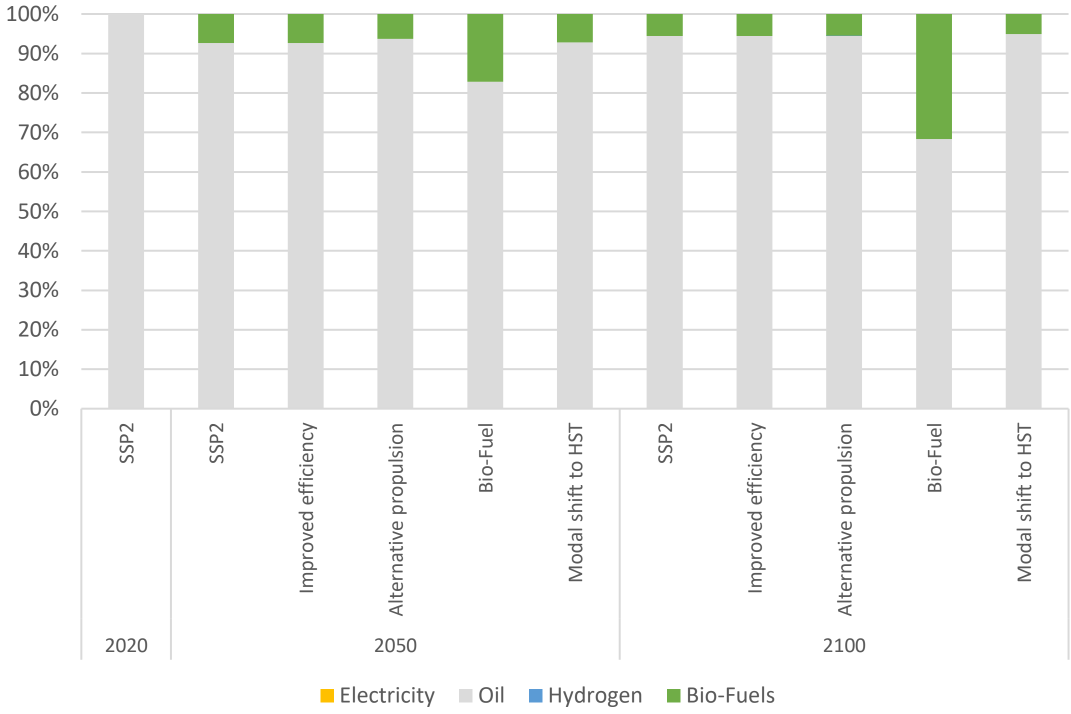

Figure 14: The share of fuel consumption of domestic and international passenger air travel in the year 2020, 2050 and 2100, based on SSP2, and the mitigation pathway scenarios: improved efficiency, modal shift to high-speed train, alternative propulsion, and bio-fuel.

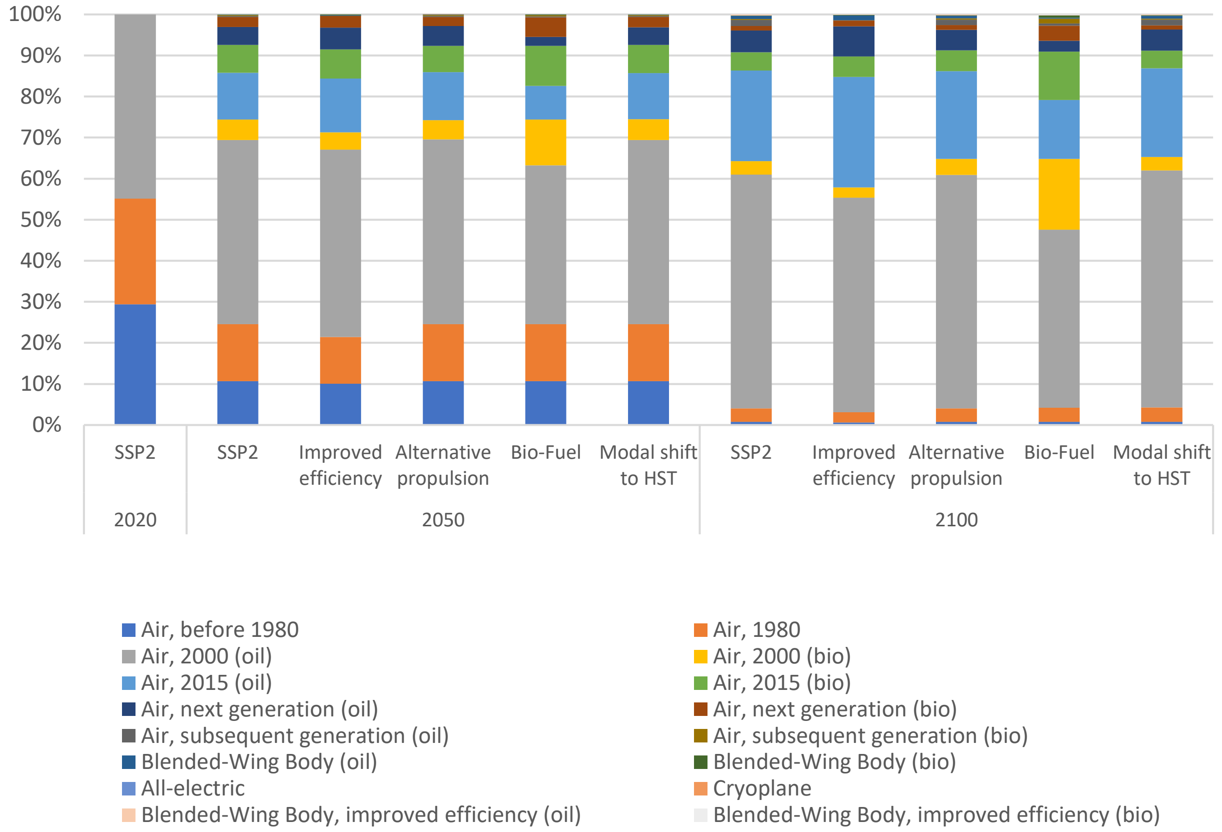

Figure 15: The fleet composition of domestic and international passenger air travel in the year 2020, 2050 and 2100, based on SSP2, and the mitigation pathway scenarios: improved efficiency, modal shift to high-speed train, alternative propulsion, and bio-fuel.

Policy target of 2.6 W/m^2 (2° C)

This second model is run with a policy target of 2.6 W/m^2 (2° C); as will be discussed below, this model corresponds a more favourable CO_2 emissions reduction in the biofuel and alternative propulsion scenario in comparison to the previous model in which no policy is implemented.

Four different mitigation pathways were run in IMAGE (Improved efficiency, Modal shift to HST, Alternative propulsion, and Bio-fuels) and compared to the baseline scenario (SSP2) in terms of CO_2 emissions, passenger air travel demand, energy use, share of fuels, and the fleet composition. In this scenario, a carbon price (as shown in Figure 2 of the Appendix) is incorporated in IMAGE to reach the climate target of 2° C. In Figure 16, the global transport emissions of domestic and international air travel and freight of the five scenarios are depicted. The major reduction is accomplished with the Bio-fuel scenario (11.4%), followed by the Modal shift to HST (7.8%) and the Alternative propulsion (6.4%). In contrast, an increase of CO_2 emissions of 1.0% is observed in the Improved efficiency scenario, potentially due to increased demand (1.9%) as shown in Figure 17. This is hypothesized to be due to reduced energy costs, as will be further examined in the discussion. Figure 17 further demonstrates a moderate increase in demand in the Bio-fuel scenario (0.4%), while the biggest reductions in travel demand are observed in the Modal shift to HST (9.7%) and Alternative propulsion scenarios (9.7%).

In Figure 18, the global energy use of domestic and international passenger air travel of the five different scenarios is shown. Interestingly, energy use in the Improved efficiency scenario increases 0.7% in comparison with the baseline while a reduction of energy use is established in the Modal shift to HST, Alternative propulsion and Bio-fuel scenarios of 9.26%, 7,6% and 0.5%, respectively. Notably, the share of oil compared to other fuels is still considerably large in each scenario, with exception of the Bio-fuel scenario, as shown in Figure 19. However, this figure can be misleading, as it shows a single time point. As Figure 27 in the Appendix reveals, the share of bio-fuel in 2090 is increased to 60%, which clarifies the immense drop in CO_2 emissions at that time, visible in Figure 16.

Furthermore, when examining the fleet composition of all the scenarios, visualized in Figure 20, it becomes clear that the more efficient airplanes dominate the market at the end of the century. However, in the Improved efficiency scenario, the most efficient airplanes (BWB improved efficiency, Air, subsequent generation) are not part of the fleet composition. Additionality, in the Alternative propulsion scenario, the all-electric and hydrogen fuelled aircrafts, are once again not part of the global fleets composition, despite the profound carbon tax included in the model. This is hypothesized to be due to their high investment costs, as later discussed.

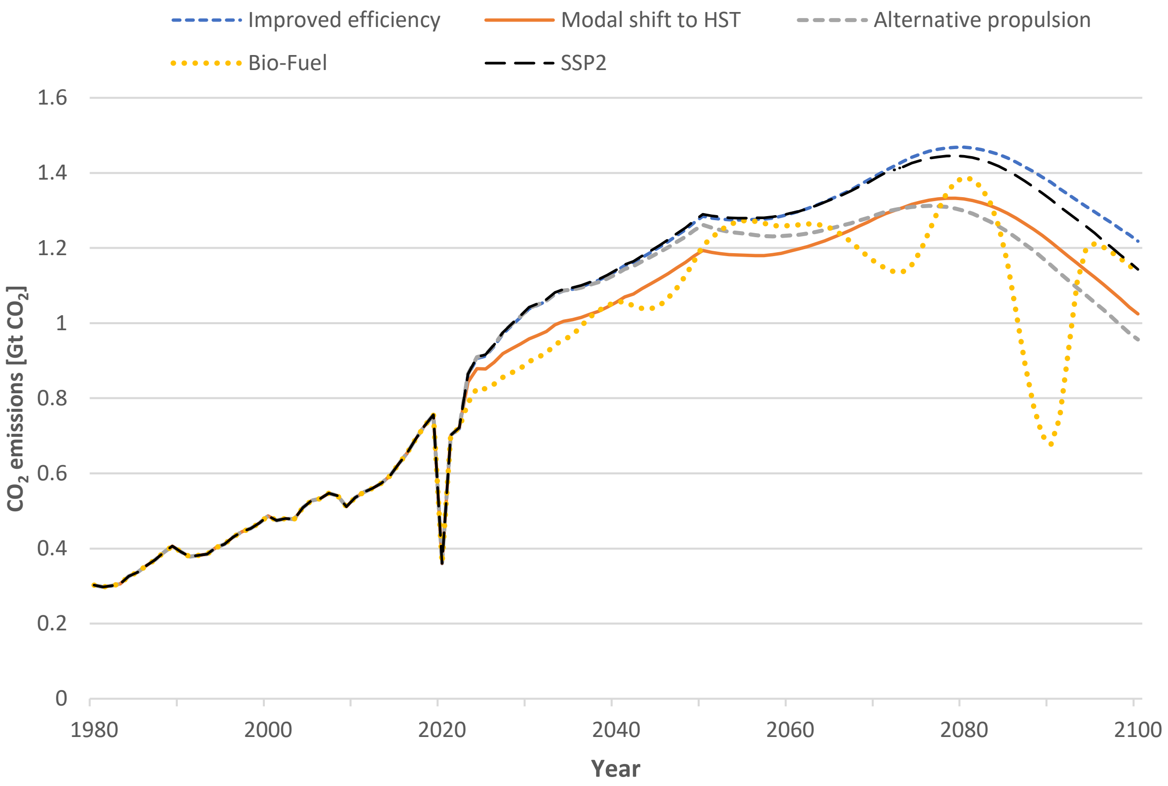

Figure 176: The global transport emissions of domestic and international passenger air travel and freight based on SSP2 with a climate target of 2.6W/m^2, in comparison with the emissions from the scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel.

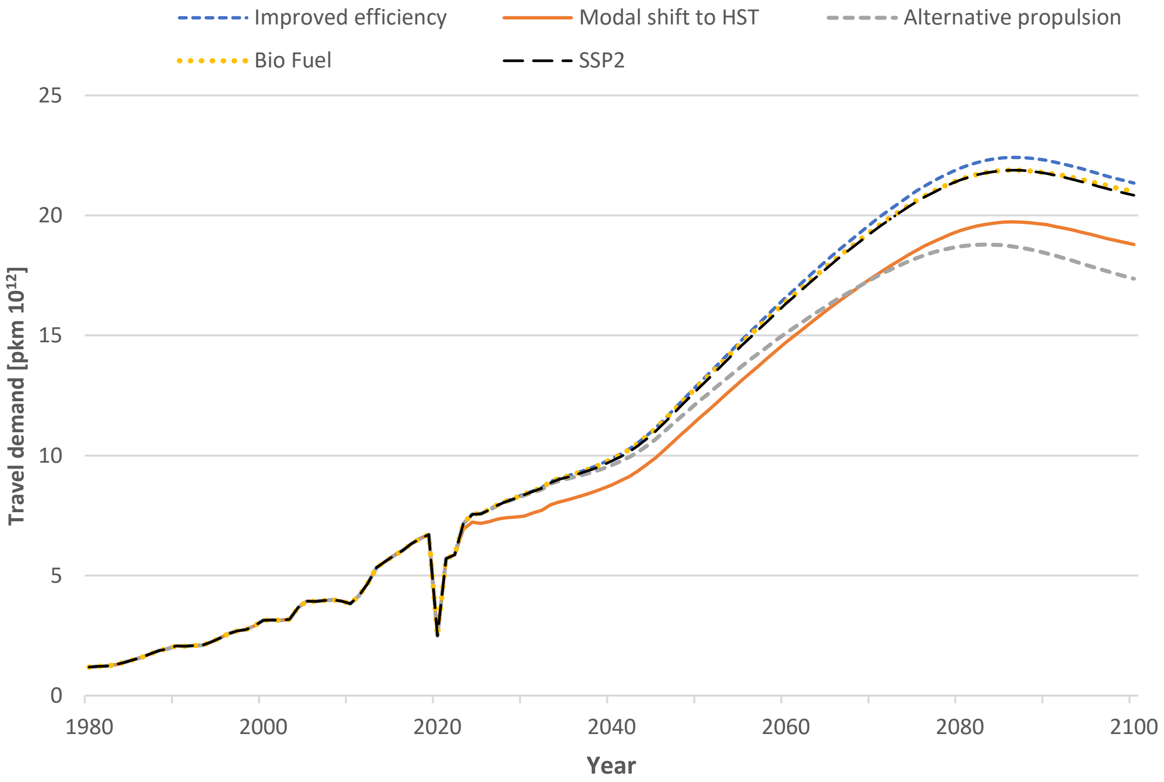

Figure 167: The global travel demand of domestic and international passenger air travel based on SSP2, with a climate target of 2.6W/m2 , in comparison with the travel demand from the scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel.

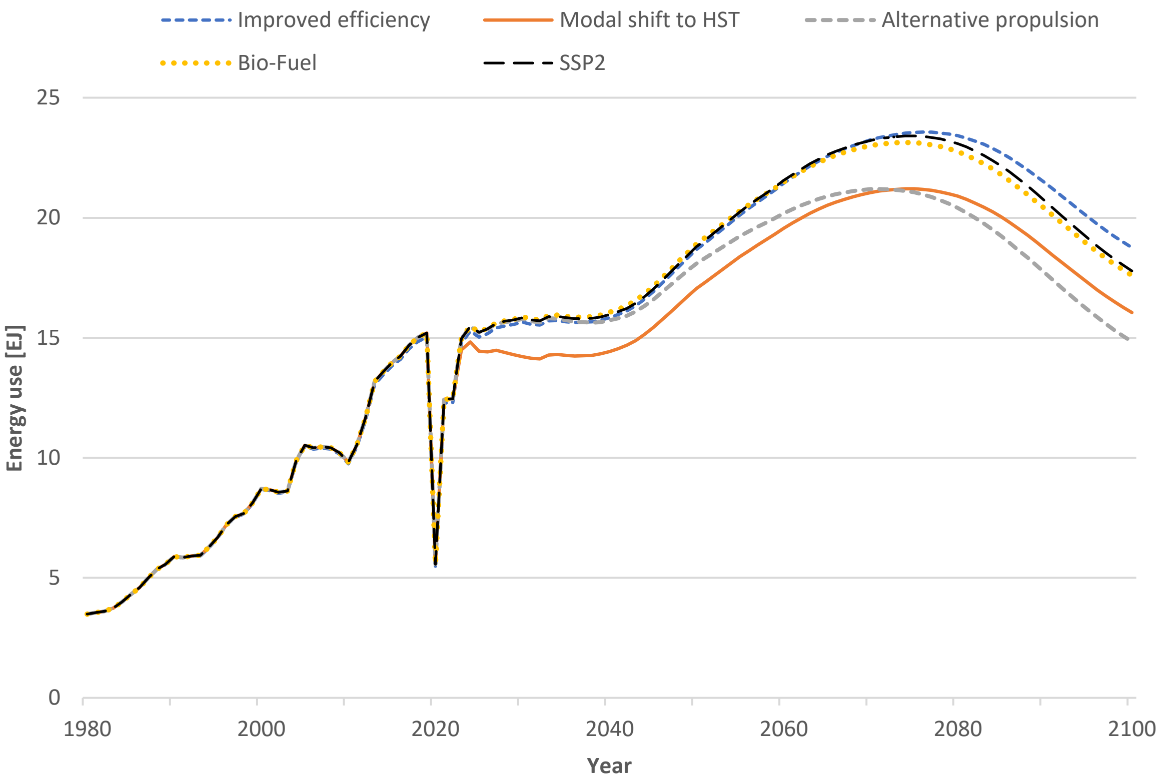

Figure 18: The global energy use of domestic and international passenger air travel based on SSP2 with a climate target of 2.6 W/m², in comparison with the energy use from the scenarios: Improved efficiency, Modal shift to highs speed train, Alternative propulsion, and Bio-fuel.

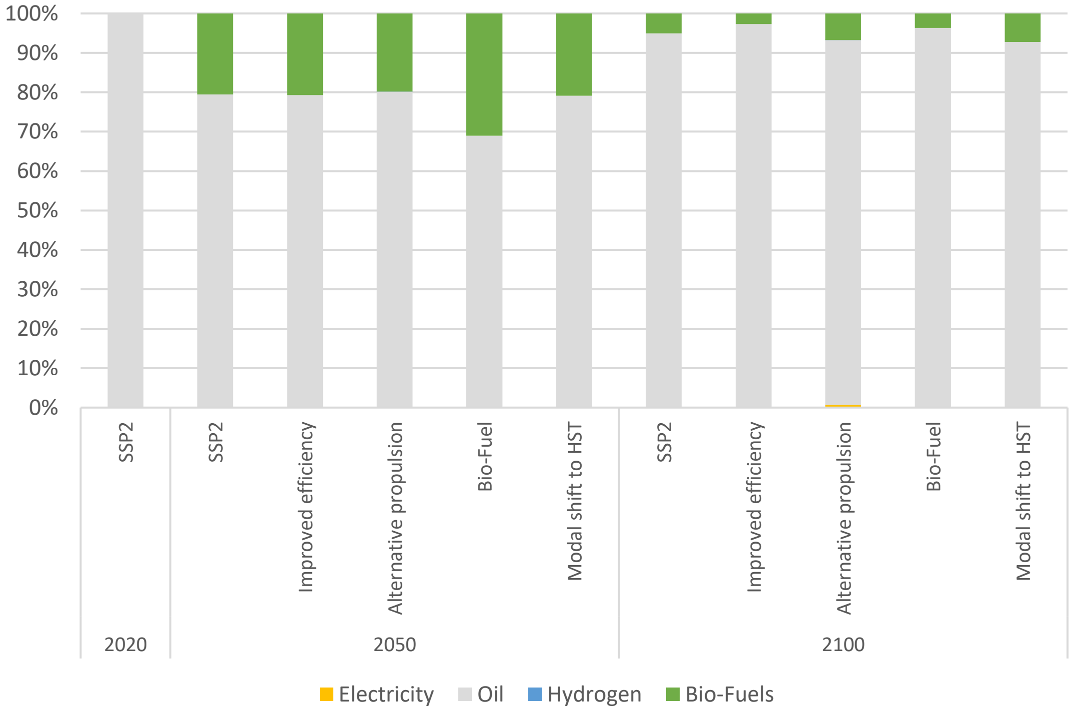

Figure 19: The share of fuel consumption of domestic and international passenger air travel in the year 2020, 2050 and 2100, based on SSP2, and the mitigation pathway scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel. Furthermore, a climate target of 2.6 W/m² is included.

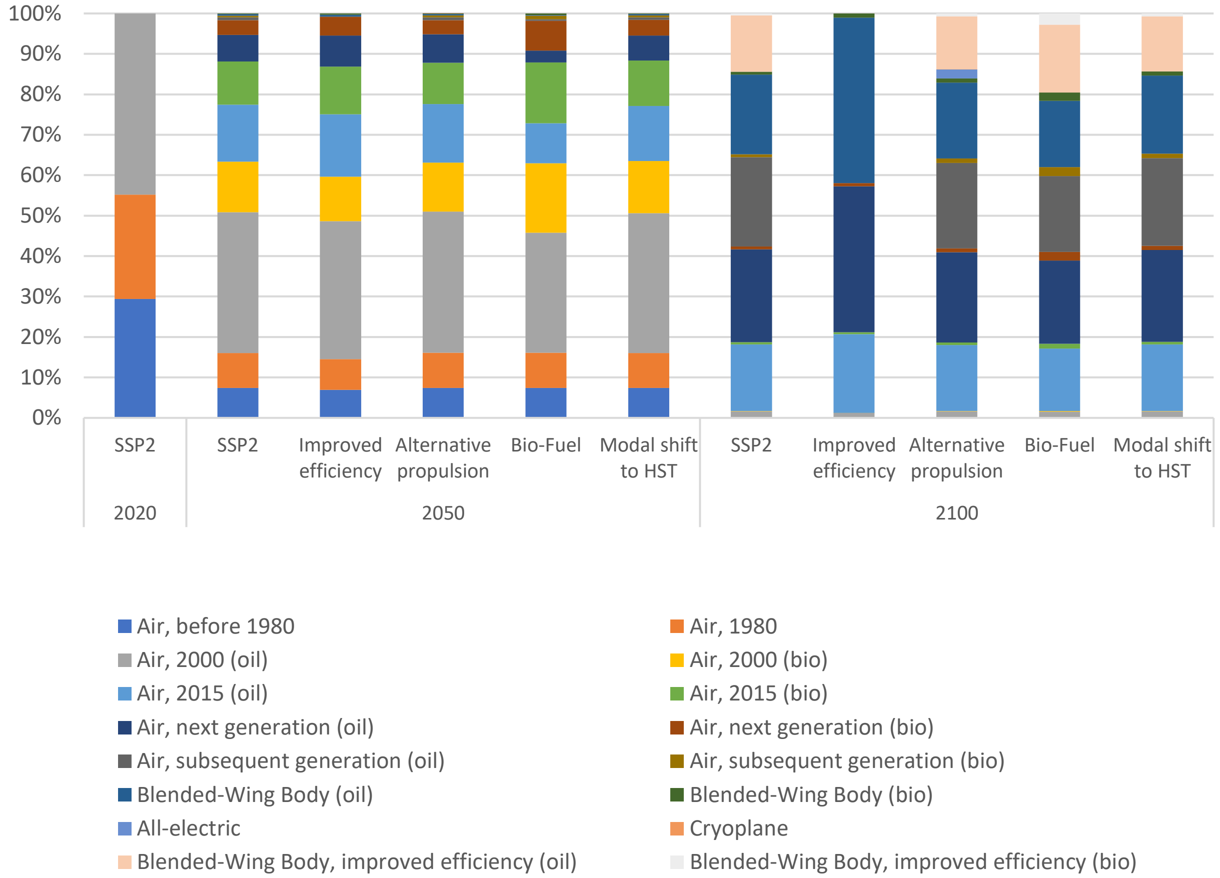

Figure 20: The fleet composition of domestic and international passenger air travel in the year 2020, 2050 and 2100, based on SSP2, and the mitigation pathway scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel. Furthermore, a climate target of 2.6 W/m^2 is included.

Policy target of 1.9 W/m^2 (1.5° C)

This third model is run with a policy target of 1.9 W/m^2 (1.5° C); as will be discussed below, this model corresponds a more favourable CO_2 emissions reduction in the biofuel scenario as compared to the model in which no policy is implemented.

Four different mitigation pathways were run in IMAGE (Improved efficiency, Modal shift to HST, Alternative propulsion, and Bio-fuels) and compared to the baseline scenario (SSP2) in terms of CO_2 emissions, passenger air travel demand, energy use, share of fuels, and the fleet composition. In this model, a carbon price (as shown in Figure 2 of the Appendix) is incorporated in IMAGE to reach the climate target of 1.5° C.

In Figure 21, the results of the five different scenarios on the global transport emissions of domestic and international passenger air travel and freight are shown. Here, it becomes clear that the biggest reduction is achieved by the Bio-fuel scenario (36.3%). The modal shift to HST reduces its emissions with 9.3%, while the Alternative propulsion scenario achieves a reduction of 5.8%. The smallest reduction is attained by the Improved efficiency scenario (1.9%), in contrast to the baseline. Furthermore, the rise of CO_2 emissions in SSP2 after 2060, is caused by a reduction of bio-fuel usage in the model.

In Figure 22, the global travel demand of domestic and international passenger air travel of the five different scenarios are shown. The Modal shift to HST reduces its demand with 9.3%, while the other scenarios all show an increase in air travel demand. The slightest increase is achieved in the alternative propulsion scenario (0.4%), followed by Improved efficiency (2.5%) and Bio-fuel (6.6%) scenarios.

In Figure 23, the global energy use of domestic and international passenger air travel of the five scenarios is presented. The scenarios Modal shift to HST, Improved efficiency, and Alternative propulsion achieve a reduction of 8,9%, 2,1% and 0,7%, respectively. Meanwhile, the Bio-fuel scenario increases its energy use with 5.5%. Interestingly, when the fleet composition is analysed (as shown in Figure 25), it is shown that this model (with a policy target of 1.9 W/m^2) is the only one where the Alternative propulsion scenario includes the hydrogen fuelled- (cryoplane) and all-electric aircrafts in its fleet. Additionality, this is the only model where the Improved efficiency scenario adopts the most efficient aircrafts. In the Bio-fuel scenario, only bio airplanes are included in the end of the century. This is further confirmed when the fuel mix of the scenarios are examined, shown in Figure 24. An overview of the reduction potential of each mitigation pathway is further specified in Table 3.

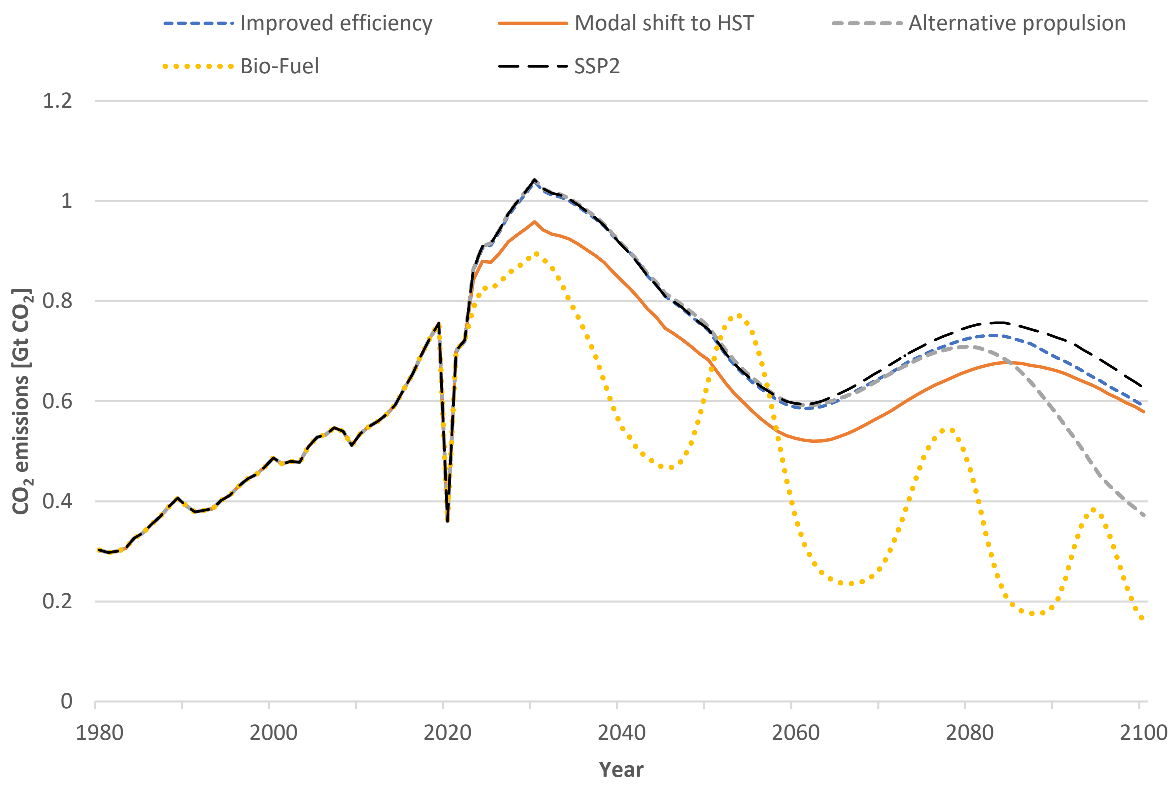

Figure 221: The global transport emissions of domestic and international passenger air travel and freight based on SSP2 with a climate target of 1.9W/m2, in comparison with the emissions from the scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel.

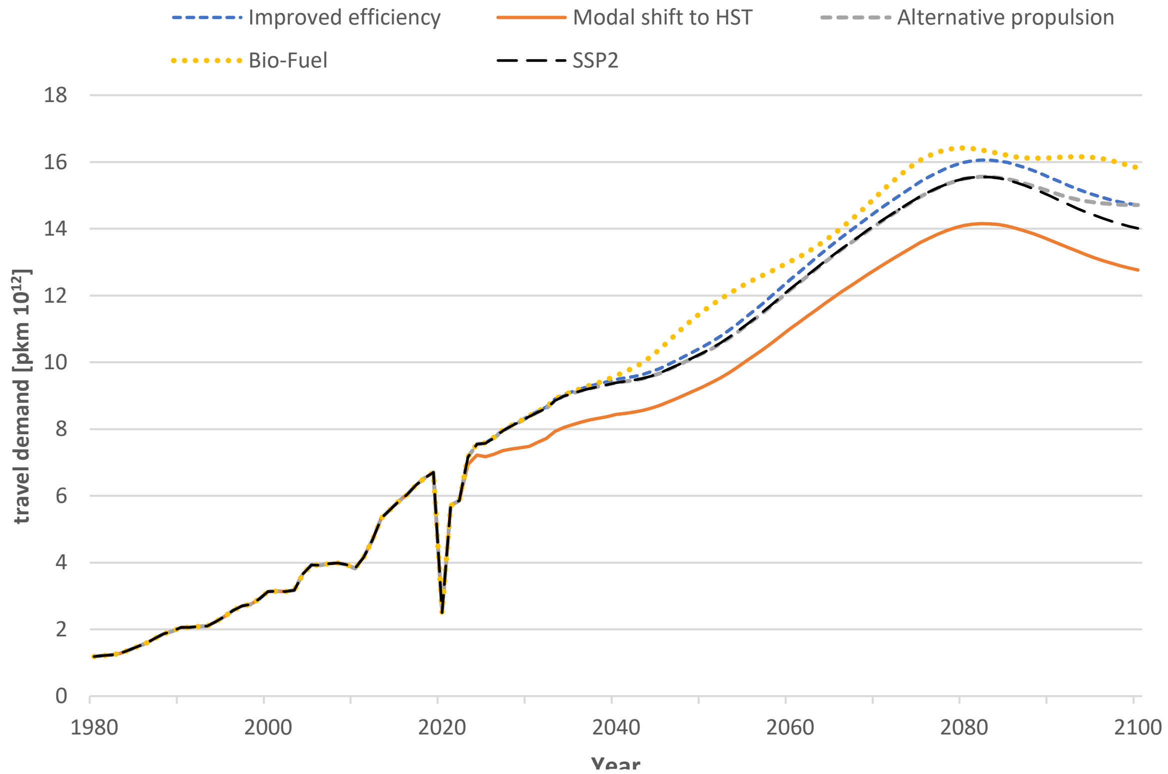

Figure 212: The global travel demand of domestic and international passenger air travel based on SSP2, with a climate target of 1.9W/m^2 , in comparison with the travel demand from the scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel

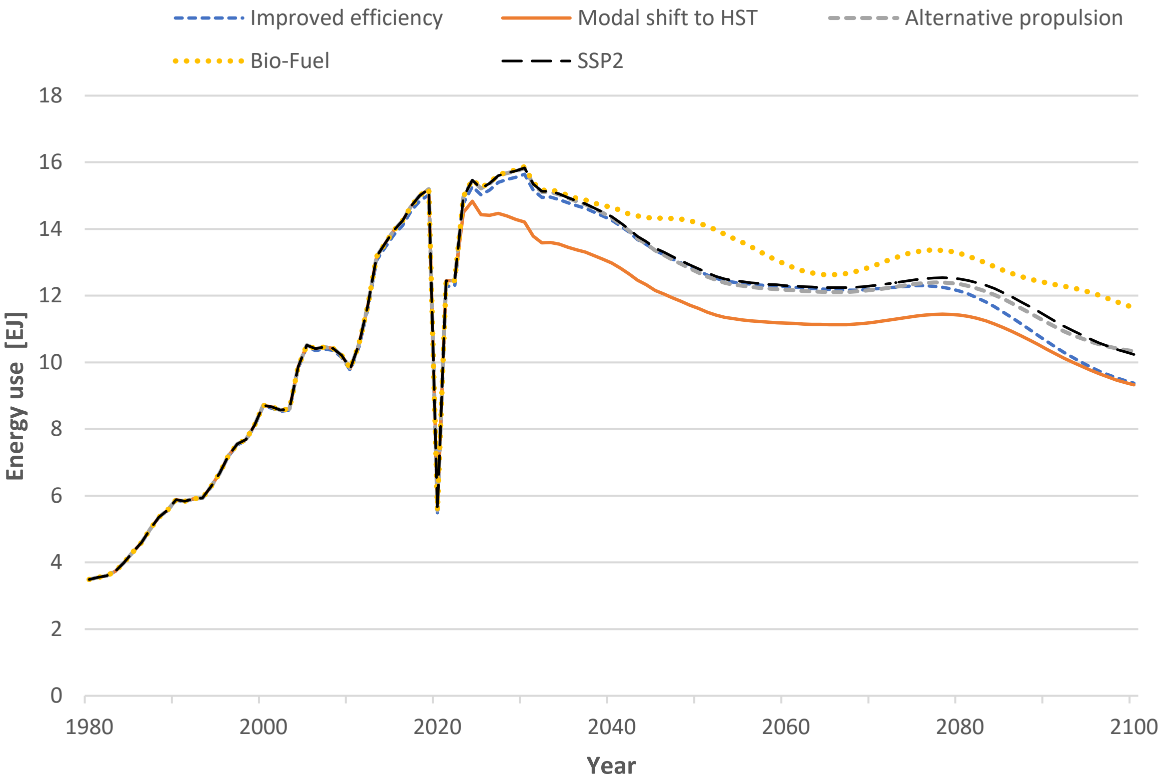

Figure 243: The global energy use of domestic and international passenger air travel based on SSP2 with a climate target of 1.9 W/m^2, in comparison with the energy use from the scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel.

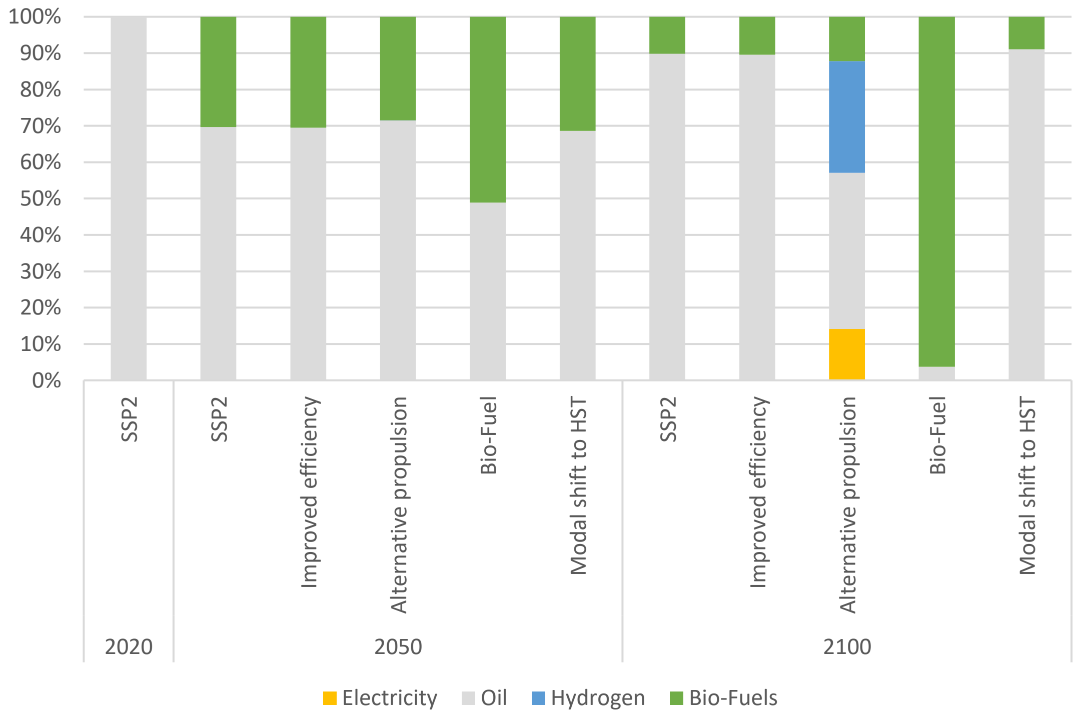

Figure 234: The share of fuel consumption of domestic and international passenger air travel in the year 2020, 2050 and 2100, based on SSP2, and the mitigation pathway scenarios: Improved efficiency, Modal shift to high-speed train, Alternative propulsion, and Bio-fuel. Furthermore, a climate target of 1.9 W/m^2 is included.

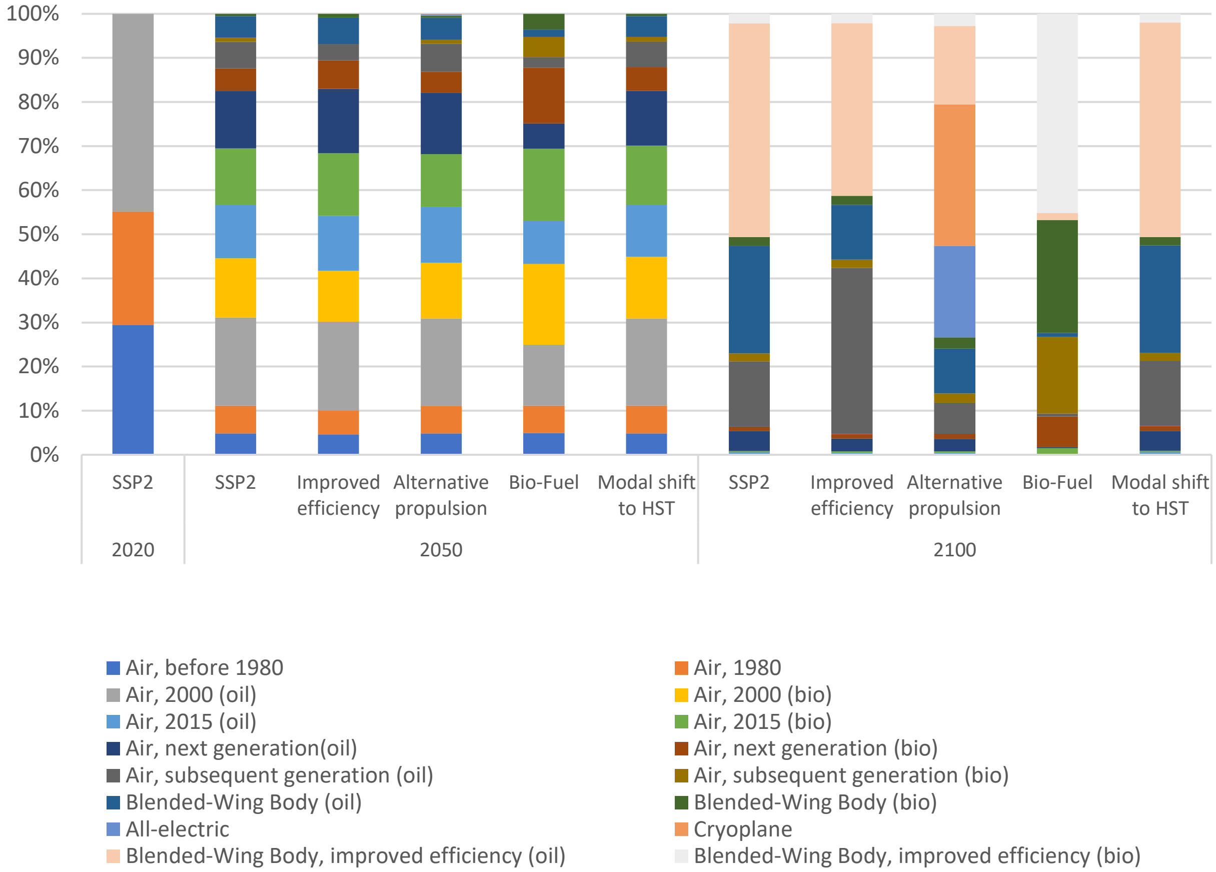

Figure 255: The fleet composition of domestic and international passenger air travel in the year 2020, 2050 and 2100, based on SSP2, and the mitigation pathway scenarios: improved efficiency, modal shift to high-speed train, alternative propulsion, and bio-fuel. Furthermore, a climate target of 1.9 W/m^2 is included.

Table 3

An overview of the CO_2 emissions, travel demand and energy use reduction potential of the mitigation pathways utilized, in comparison with a baseline SSP2 scenario, when no policy or a climate target is incorporated in IMAGE

		No policy	**Climate target of 2° C**	**Climate target of 1.5° C**
CO_2 emissions reduction (%)	*Improved efficiency*	1.3	-1.0	1.9
	Alternative propulsion	0.9	6.4	5.8
	Bio-Fuel	6.8	11.4	36.3
	Modal shift to HST	7.3	7.8	9.3
Travel demand reduction (%)	*Improved efficiency*	-1.3	-1.9	-2.5
	Alternative propulsion	2.8	9.7	-0.4
	Bio-Fuel	0.23	-0.4	-6.6
	Modal shift to HST	9.6	9.7	9.3
Energy use reduction (%)	*Improved efficiency*	1.5	-0.7	2.1
	Alternative propulsion	2.1	7.6	0.7
	Bio-Fuel	0.17	0.5	-5.5
	Modal shift to HST	9.0	9.26	8.9

5. Discussion

Through utilization of an updated version of the internationally recognized IMAGE model, this study gives an elaborate insight in how different scenarios, demand and technological change may contribute to the decarbonization of the aviation sector. The results give an innovative contribution to the current literature on this topic, as they robustly demonstrate how individual strategies may aid in reducing global CO_2 emissions, which is relevant for debating policy tactics and evaluating the relevance of different technologies.

Interestingly, the predicted air travel demand in this study is remarkably lower compared to that predicted in previous research. For instance, the Global Market Forecast by Airbus (2019) which analyses the expected trends in the aviation and demand for passenger air travel, expects an annual compound growth of 4.3% in pkm from 2019 to 2038, resulting in 13.37 tera pkm in 2030 (Airbus, 2019). In contrast, the SSP2 model in this study in IMAGE shows a lower activity level of 8.5 tera pkm in that same year. While the Airbus' forecast may seem excessive, outlooks in the past conducted by Airbus on the global demand of air travel were predicted accurately. Furthermore, findings by Airbus are in line with a previous study by Dray et al. (2019), which used an Aviation Integrated Model to project the sectors behaviour on various variables, such as activity or direct CO_2 emissions. Here, an activity level based on a SSP2 scenario of 12.7 tera pkm is expected in 2030, and this activity level grows to 26.62 tera pkm in 2050. In comparison, IMAGE reveals a passenger travel demand of 13.9 tera pkm in 2050, which is a difference of almost 47.78 %.

Important to note, is that both the study by Airbus and Dray et al. (2019) made these predictions before the COVID-19 pandemic struck, an event that resulted in a decline in the global economy and activity in global air travel demand. A study by Gössling et al. (2021), which was conducted after the pandemic, has assessed pkm development of the global aviation sector in case the activity level prior to COVID-19 is restored in 2024. Of note, this study was done with different assumptions than the current IMAGE model as they included a feed-in quota for synthetic aviation fuels with a price elasticity of -0.75, thus are hard to compare. In the study, an activity level of around 9.6 tera pkm is expected in 2030. However, the activity is predicted to grow back to 22.5 tera pkm in 2050. A critical note on this study, would be that the growth projections are based on the aviation industries market forecast, which make them ambiguous as these projections may have self-serving intentions. This was also observed by Becken & Carmignani (2020), who question the expectations for growing air travel demand predicted by the industry. Their study reveals that the industry underestimates the rising cost of carbon and declining socio-economic factors due to climate change. Furthermore, they show that a growth rate of 4.3% of air travel demand can only be obtained if the price elasticity decreases to -1, and the income elasticity is 1.8. This value for income elasticity is well above what is estimated in scientific literature. Nevertheless, the difference in projections of air travel demand between the SSP2 scenario derived from IMAGE and the studies previously described are significant and should be further analysed in future studies. If indeed the activity level of global air travel demand in 2050 would rise to 26.62 tera pkm, the projected CO_2 emissions in IMAGE would increase from 2.06 to 3.08 Gt in that same year, making the sector even more problematic to decarbonize.

A surprising finding in the current study, is that the Improved efficiency scenario (showing the impact of the ICAO 2% target of annual fuel efficiency improvement), hardly leads to a reduction of GHG emissions. A reduction of GHG emissions would be expected, as this is also observed in current scientific literature. For example, Hasan et al. (2021) indicate a reduction of 6.3% in comparison with their baseline scenario, however, this is with the assumption that no rebound effect of an increasing travel demand would take place, due to lower ticket prices caused by the improved efficiency. The current study demonstrates that improved efficiency led to a slight increase in travel demand (with and without a climate target included in IMAGE). An explanation could be that since the energy efficiency of the fleet is improved, the $EnergyCosts$ are reduced. This results in a lower $CostPerPkm$ for the air travel mode, which results in an increase in travel demand. However, the technologies to which the efficiency improvement is related (Air, subsequent generation; BWB, improved efficiency) are only introduced in the global fleet composition if a climate target of 1.5°C is incorporated, most likely due to their high costs. This raises the question if the current method correctly demonstrates the impact of this improved efficiency target as this impact can only be evaluated for one scenario. Nevertheless, in the 1.5°C scenario, the improved efficiency of the technologies in question result in a minor increase in air travel demand (2.5%) and a small decrease of CO_2 reduction (1.9%). This result shows the limited opportunity to reduce the GHG emissions of the sector through improved efficiency of the fleet, since a rebound effect in travel demand does seem to take place. A solution to this event, could be the introduction of a harmonized global ticket tax on air transport, as is suggested in a study by Peeters (2019). He demonstrated that a ticket tax on air transport, reduces the air travel demand, which would increase the reduction potential of the improved efficiency of air travel.

An important finding, is that there seems to be a limited possibility of all-electric and hydrogen fuelled aircrafts to reduce GHG emissions in the aviation sector, irrespective of policies implemented. This could, in part, be explained by the fact that both technologies are only suited for short- and medium travel distances, which reduces the potential on GHG reduction. Crucially however, are their high investment costs in comparison with other aircraft technologies. Due to this, all-electric and hydrogen fuelled aircrafts are only adopted in the global fleet composition if a significant carbon tax is included in IMAGE. Notably, information about the estimated investment costs of these technologies is still highly uncertain. In this thesis, a technology-cost relationship as proposed by Lee et al. (2001) is utilized to identify the possible investment costs. This relationship is based on the direct operating cost per revenue passenger kilometre versus fuel efficiency of 31 selected aircrafts during the period 1968-1998. One could argue, that this technology-cost relationship does not apply to these fundamental different aircraft technologies, but due to a lack of costs estimations in scientific literature, this relationship is considered to be just.

Which is not taken into account in this study, is that all-electric and hydrogen fuelled aircrafts also require extensive infrastructure changes (Dray et al., 2018). This could even lead to an underestimation of the predicted investment costs to implement these technologies. Nevertheless, these technologies are only considered to be feasible in the coming decades, which allows time for breakthroughs in battery technologies. If a battery-pack of 1,600 Wh kg^{-1} would become a possibility, the operating distances of an all-electric airplanes rises to 2,222 km (Schäfer et al., 2019). If that is the case, it is estimated that 80% of all airport departures could be flown with all-electric aircrafts, while reducing fuel use and direct CO_2 emissions by around 40%. Such breakthroughs in technology would seriously affect the reduction potential. The same logic holds for hydrogen fuelled aircrafts. In this study, it is assumed that these aircrafts are only capable to fly medium-distance flights trips (<1421 km), while in a study by McKinsey (2020) it is believed that even long-ranges flights up to 10,000 km are possible. However, due to the increased take of weight caused by the hydrogen tanks, the energy demand increases with 42%, while the additional cost rises with 50%. However, if the productions costs of hydrogen would markedly drop in the coming decades, for instance due to large investments in R&D, the reduction potential of hydrogen aircrafts could increase since the expected flight distance is improved significantly.

Another unexpected finding in the current study, was that travel demand decreased in the Alternative propulsion scenario (the scenario that includes all-electric and hydrogen fuelled aircrafts) even though the technologies were not included in the global fleet. It is interesting to wonder how these technologies can affect travel demand if not implemented at all. In the model, a potential explanation of this reduction can be found in the increased $CostPerPkm$ of the air travel mode due to the introduction of the alternative propulsion technologies. Since the investment costs of all- electric and hydrogen aircrafts are more expensive, the average cost of air travel becomes higher due to a rise in $AddTechCost$. Consequently, other transport modes are preferred in the model due to the lower costs to travel, which results in a reduction of air travel demand.

Results concerning the modal shift to HST scenario, reveal a reduction potential of GHG emissions between 7.3% and 9.3%, depending on a climate target included or not. These findings corresponds to a study from Prussi & Lonza (2018), in which GHG savings between 4% and 21.6% are observed in case 5% or 25% of the expected aviation growth on the analysed routes in Europe are substituted with HST. It should be noted however, that the current study assumes that the short-distance passenger air travel is replaced with HST on a *global* scale and that the infrastructure for this shift to HST actually exists. Thus, our data could be an overestimation. Furthermore, if this mode shift occurs, it also negatively impacts the potential of all-electric and hydrogen-fuelled aircrafts, since these technologies are also limited to these short-distance trips.

The greatest potential for GHG savings of all the mitigation pathways, is represented by the Bio-fuel scenario. If no policy is included, the implementation of biofuels leads to a reduction of 6.8% in GHG emissions. With a climate target of 2°C or 1.5°C incorporated, a reduction of 11.4% and 36,6% is shown. These findings validate the importance of sustainable aviation fuels to mitigate climate emissions in the aviation sector. The biggest advantages of these drop-in fuels is the ability to possess the same functionality to fossil jet kerosine, so no modifications in today aircrafts or engines is needed (Bauen et al., 2020). Furthermore, the technology status of the production route of biofuels produced from vegetable oils and animal fats have reached commercial levels, making the fuel an economically viable option. Fourth-generation biofuels (sourced from algae) are being developed and do not compete with conventional crops for land use (Azami et al., 2019). Sustainable aviation fuels are also considered to be the only solution to reduce GHG emissions for long distance flights. However, several constraints are seen. For instance, the reduction potential strongly depends on the feedstock and conversion routes used to produce bio-based jet fuel. Furthermore, some studies suggest that the uprising demand of bio based jet fuel is responsible for afforestation issues, resulting in biodiversity loss and affecting the fertility of the soil, which will cause an increase in CO_2 (Kandaramath Hari et al., 2015). These factors must be further explored and taken into account in future analyses.

All in all, the results of the emission potentials of the evaluated mitigation pathways reveals the challenge in which the aviation sector is embedded today. If no policy is assumed, the projected CO_2 emissions continue to rise in an unprecedented fashion, even with the mitigation pathways included. If the concentration pathway level of 2.6 W/m^2 is included in the model, CO_2 emissions will still rise in the coming decades. Only when a profound carbon tax is incorporated in IMAGE to reach the climate target of 1.5°C, an overall decline in CO_2 emissions is observed. While implementing bio-fuels may reduce emissions considerably, net zero emissions by the sector is never achieved in any one of the scenarios. Even when a scenario is run in which the mitigation pathways are combined, which in itself is already questionable as some mitigation pathways compete with one another (i.e. Modal shift to HST and Alternative propulsion), net emissions do not reach zero. These results highlight that realising full decarbonisation of the aviation sector is particularly hard to achieve.

Limitations

This research has also several limitations. First of all, no sensitivity analysis was conducted. The results are based on the estimated efficiencies and costs of aircraft technologies, which are subject to change in the future. As these variables are uncertain, the reliability and validity of the findings would be reinforced through a sensitivity analysis. Without this analysis, it is unknown whether results would fluctuate considerably if the input data varies. For example, if the investment costs of alternative propulsion technologies are lowered in the model, it would be interesting to analyse how this would affect the possibility to enter the global aviation market, and thereby reduce GHG emissions.

Furthermore, this study did not evaluate the potential impact of the COVID-19 pandemic on the development of air travel demand, yet it is highly suggested to be included in further research. As a study by Suau-Sanchez et al. (2020) shows, the recovery of business travel is expected to be highly uncertain, since teleworking has increased immensely. According to Gössling & Humpe (2020), 71% of the total flights are commercial air travellers, while 10% of those fliers may be accountable for 30-50% of all flights taken. If only a small amount of these fliers are business travellers, this potential decline in air travel demand could seriously affect the related CO_2 emissions.

Another limitation is the scope of the mitigation pathways included in the study. While most prominent pathways are included, additional demand and technological changes are mentioned in scientific literature yet not included in IMAGE. As stated, the advantages of renewable drop-in kerosene alternatives, such as bio-fuel, are deemed to have a major impact on the reduction of GHG emissions. Another important candidate in this category, is the Power-to-Liquid (PtL) aviation fuel. It is normally produced with a Fischer-tropsch or a methanol synthesis by combining a concentrated source of CO_2 with electricity and water (Bauen et al., 2020). PtL is considered to be an attractive solution, since it has less feedstock constrains and sustainability issues compared to bio-based fuels (Bauen et al., 2020). In a scenario study by Hasan et al. (2021), a reduction of 66.5% is achieved of the required emissions target in 2050 if the share of PtL in the aviation energy mix is increased with 44%. However, the technology status of this fuel is still in the demonstration phase and projections of future productions costs remain unclear (Schmidt et al., 2018). Furthermore, to implement the large-scale production of this fuel, a serious cost reduction of the production of renewable hydrogen is required. Nevertheless, the incorporation of PtL in IMAGE to further understand the potentials of this sustainable aviation fuel to decarbonize the aviation sector is believed to have great potential and is therefore defined as an interesting topic for further research. Other mitigation pathway that are promising, are fleet modernization (replacing old aircrafts with more efficient ones) and the improvement of air traffic management (Hasan et al., 2021). While both methods are consisted to have a significant impact on abated CO_2 emissions, the marginal abetment costs are substantial.

6. Conclusion

This study aims to give an insight on the decarbonization potential and limits of the global aviation sector through the following research question:

> *"How could the aviation sector contribute towards reaching the climate goals as stated in the Paris Agreement of 2015?"*

Firstly, the most important drivers of global demand for air travel are identified. It is recognized that income growth approximated through GDP, in combination with population growth, are considered to be key drivers of global demand for air travel. When a reduction of travel demand is desirable, to reduce GHG emissions, these drivers are essential to take into account.

Secondly, the most crucial pathways to mitigate emissions in the aviation sector are examined by reviewing of current literature. One of the major pathways is the usage of sustainable aviation fuels, instead of fossil-based jet fuel. Renewable drop-in kerosine, such as bio-fuels, are considered to be an appealing option for the aviation sector as these types of fuels require no modification on the aircrafts engine, airframe and refuelling infrastructure. However, the productions costs are relatively high in comparison with the fossil kerosine fuel jet, thus it is hypothesized that strong policy support would be needed to support the uptake of these fuels. Furthermore, the potential on GHG reduction is still debated and depends strongly on the feedstock and conversion processes applied. Another essential mitigation pathway identified, is the introduction of alternative propulsion technologies on the aviation market, such as all-electric aircrafts or hydrogen-fuelled aircrafts. The major advantages of these technologies, is the potential to eliminate direct and indirect climate emissions, in case of all-electric aircrafts, or to reduce them significantly. However, the dependency on trip distance remains a foremost barrier to decarbonize the aviation sector as a whole. Furthermore, the improvement of the efficiency of the aviation fleet through technological innovation is considered to be an important contributor to reduce GHG emissions, since the energy and carbon intensity of the sector declines. The reduction of air travel demand is believed to be equally significant, which can be accomplished to switch short-distance passenger air travel towards the transport mode high-speed train. Thus, these four different pathways are integrated into IMAGE, to develop scenarios in which a deeper insight is gained on how the demand and technological change in the aviation sector contribute to emissions mitigation.

Before running the different scenario's in IMAGE, the model is updated by improving the representation of the aviation sector. In the updated model, a more precise categorization of different aircraft types is included. Furthermore, data on efficiency and investments costs were renewed as based on current literature. Moreover, trip distance for hydrogen and all electric aircrafts were programmed to be limited to short- and medium distances for a more accurate representation of reality.

Running different scenarios in the updated model of IMAGE, demonstrates that the greatest reduction of CO_2 emissions is obtained when a switch from jet-fuel to bio-fuel is provided. This is the case when no policy target is included in IMAGE, but also when policies are included specified to reach the climate targets of 2° C and 1.5° C. Interestingly, the model also demonstrated that that travel demand seemed practically unaffected by the biofuel mitigation pathway. In the 1.5° C scenario, an increase in passenger air travel demand is even observed. A notable finding is that the potential of hydrogen- and all-electric aircrafts on climate change mitigation in the aviation sector appears to be marginal. The technologies are hypothesized to be too expensive. Only if the climate target of 1.5° C is met, these aircrafts are included in the fleet composition, making them of no importance yet in other scenarios. On top of this, the total achievable market share of these technologies is constrained as trip distances are restricted. It should be noted, however, that when hydrogen- and all-electric aircrafts are included in the 1.5° C scenario, they cause a markable drop in CO_2 emissions.

Interestingly, a modal shift from short-distance air travel to high speed train shows a reduction potential around 7.3~9% on global CO_2 emissions on the aviation sector, and a similar drop in passenger air travel demand. Of note, the assumption is made that HST infrastructure exists to replace short-distance air travel. Lastly, if the aviation fleet would undergo a 2% efficiency improvement per year on the aviation fleet, the data in this study shows that this would have little impact on CO_2 emission reduction. Without a climate policy, CO_2 emissions are minor with travel demand even increasing slightly. With a climate policy of 2° C integrated in the model, both the domestic and international air travel demand and the CO_2 emissions increased. This phenomenon shows the importance of additional policy measures on top of those modelled in this study, such as a harmonized air passenger tax system that increases if the distance flown is increased.

This study shows the relevance and importance of IAMs to better understand how the aviation sector can contribute towards reaching the climate goals as stated in the Paris Agreement of 2015. The scenarios developed shows the challenge in which the sector is detained today. Not a single mitigation pathway is the answer to reach net zero CO_2 emissions nor a combination of those conducted in this study. Even with a significant carbon tax incorporated in the model, achieving net zero emissions by the end of this century seems practically unreachable. If the climate mitigation challenge is to taken seriously, more scientific research as well as serious R&D efforts from the sector itself, are needed to further understand how the aviation sector could potentially be decarbonized. Only then, will humanity eventually be able to leave the fossil fuelled economy behind, while flying towards a better and brighter future.

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8. Appendix

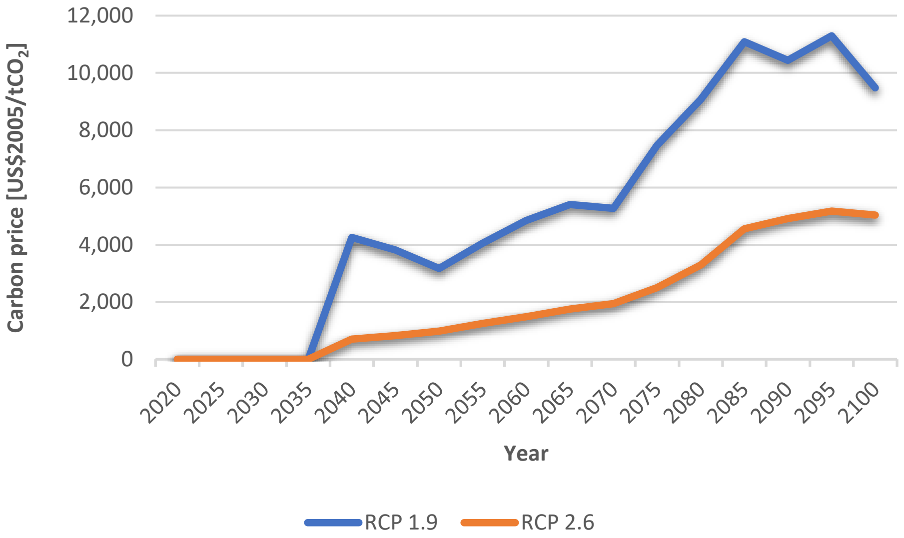

Figure 266: The global carbon price utilized in the mitigation scenarios based on a representative concentration pathway (RCP) of 2.6W/m^2 and 1.9 W/m^2 in the year 2100, corresponding to a climate target of 2° and 1.5°, respectively

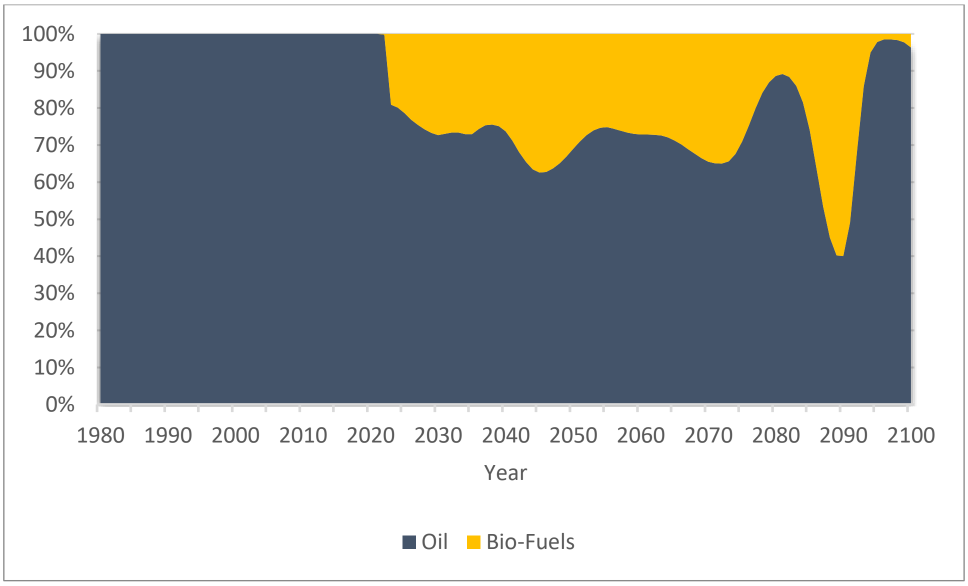

Figure 277: Fuel use share of domestic and international passenger air travel and freight in the Bio-fuel scenario, with a climate policy of 2.6W/m^2 included.