Techno-economic Analysis of Sustainable Aviation Fuels by Using Traffic Forecasts and Fuel Price Projections

A Case Study at TUI Aviation

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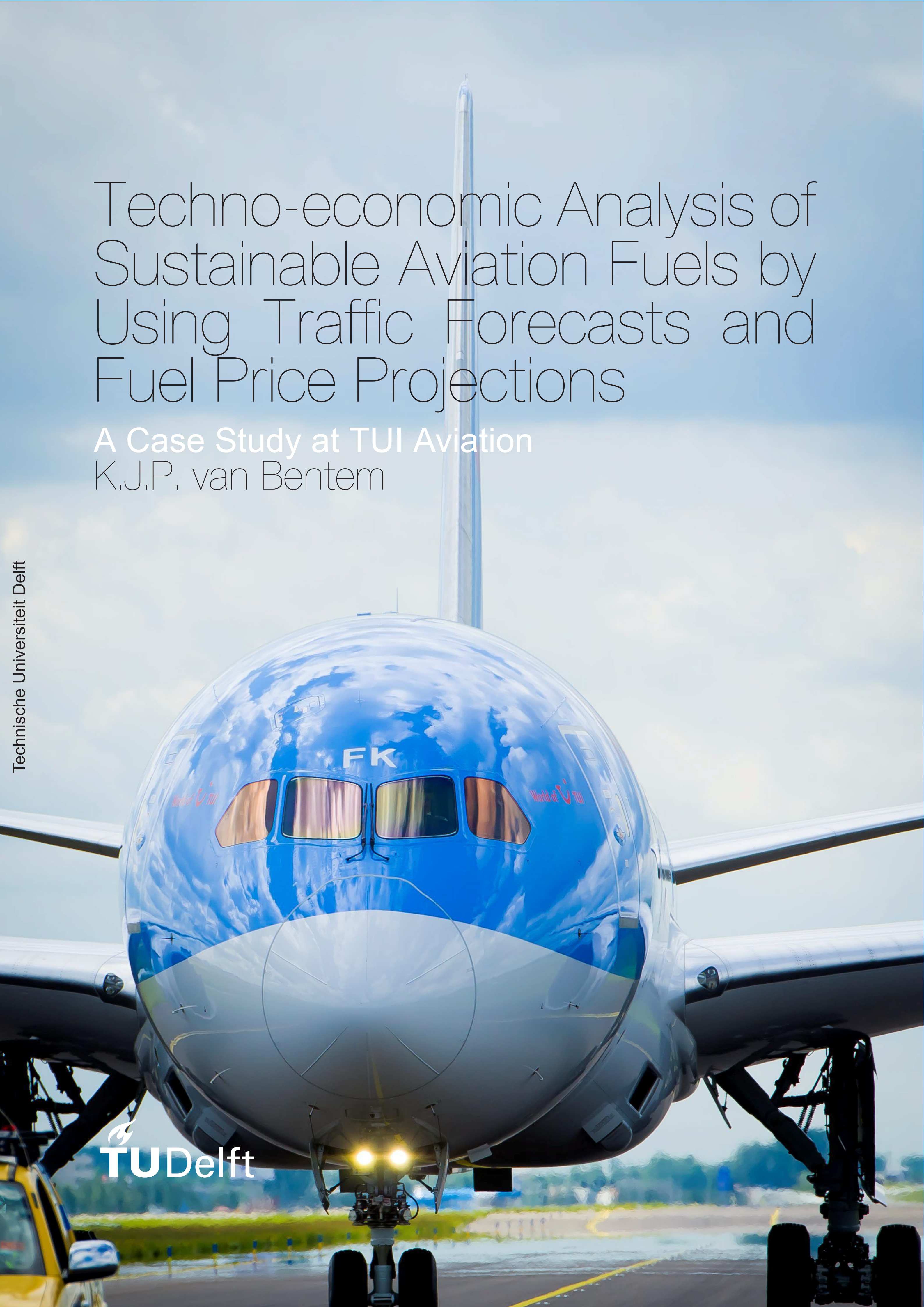

TU Delft

Techno-economic Analysis of Sustainable Aviation Fuels by Using Traffic Forecasts and Fuel Price Projections

A Case Study at TUI Aviation

by

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Executive Summary

Introduction

The total oil demand share of aviation in the transportation sector is 11.2%, which ensures aviation is the second major oil consumer. The International Civil Aviation Organization (ICAO) expects that annual CO_2 emissions would grow by more than 300% by 2050 without additional measures. A solution is to introduce Sustainable Aviation Fuel (SAF), which is made from non-fossil feedstock. The use of Sustainable Aviation Fuels (SAF) would reduce greenhouse effects, reduce fossil oil dependency, improve air quality and create new job opportunities.

Previous research focused on the technological feasibility of SAF, or the urgency to implement SAF, but little research has been done into the economic feasibility of SAF. There is a research gap that compares all relevant SAF alternatives into one research. Additionally, no research has been found that states the increase of SAF production and how this would influence future prices of SAF alternatives. Combining these factors into one research would give a clear and complete view of the attractiveness of SAF alternatives for the aviation industry.

This research aims to determine which Sustainable Aviation Fuels are most attractive in a social and business perspective. The most attractive fuel in a social perspective is the one that could ensure the largest carbon mitigation potential. The most attractive fuel in a business perspective is determined by delivering the Net Present Value of the investment needed for implementing each existing SAF alternative. Therefore, the research question is:

> What are potential attractive SAF alternatives in a social and business perspective?

Methodology

The research starts with a stakeholder analysis to determine the main policies and regulations regarding carbon mitigation in commercial aviation to determine a carbon goal. To determine the expected SAF offtake quantities, a traffic and CO_2 forecast was made for the period 2020-2050, considering the COVID-19 crisis and external factors that reduce future CO_2 emissions (technology and operations, green area in Figure 2). The gap between the CO_2 forecast and the carbon goal needs to be filled by introducing SAF (blue area in Figure 2). Each of the SAF alternatives has its characteristics, like emissions reduction and cost. Then, the SAF quantities and associated costs required to fill this gap can be determined, leading to a Net Present Value of investment needed for each of the SAF alternatives separately.

This research is done by doing a case study at TUI Aviation. Their role is to provide air traffic demand data and CO_2 data that are related to that demand, so that the model and the outcome of this research match reality as closely as possible. This may result in new scientific insights into the subject, and it could propose courses of action for TUI Aviation to limit carbon emissions. The outcome of this research will be a leading source in the development of a SAF implementation strategy within the TUI Group.

Primarily, literature has been used to collect all relevant data regarding the traffic forecast, SAF characteristics, and stakeholder goals and regulations. Operational data of 2019 is retrieved from the TUI Aviation database and used to measure air traffic and CO_2 emissions in 2019. Data analysis methods include the use of the CO_2 emissions forecasting method from the Air Transport Action Group, traffic forecasting methods, the experience curve method (with learning and scaling effects) to determine future SAF prices by cumulative production increase, and a Cost-Benefit Analysis.

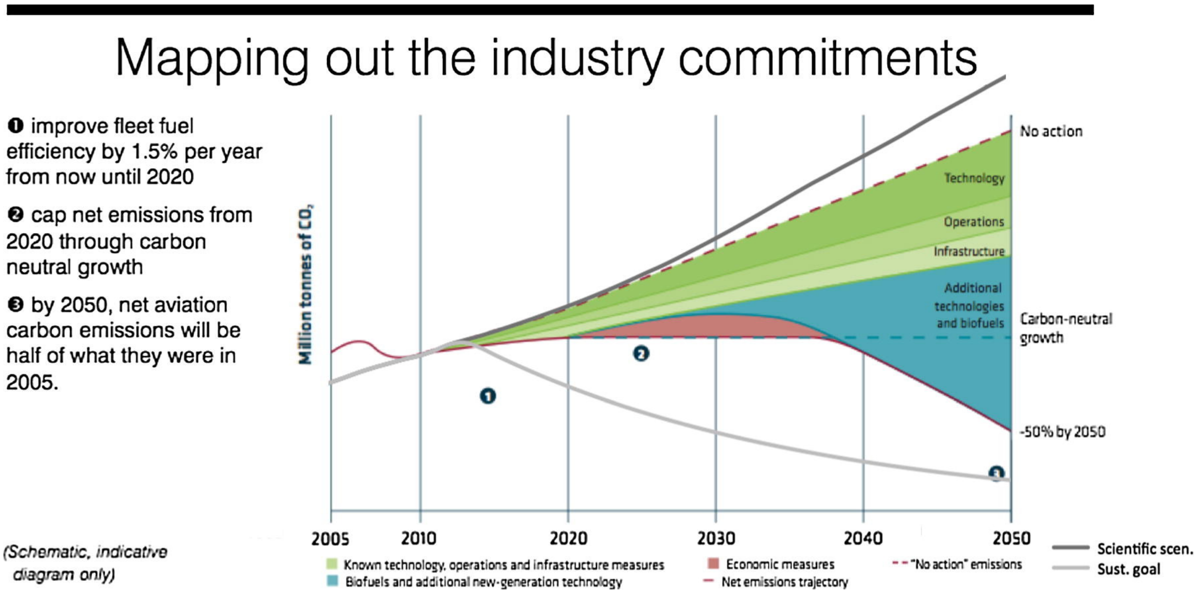

Figure 2: Long term targets for international aviation CO_2 emissions. Adapted from Peeters et al. [96]

Policy foundation

The airline industry generally embraces two goals. The International Air Transport Association (IATA) promised to emit 50% fewer carbon emissions in 2050 than the industry's 2005 emissions. However, some airlines further than that and commit to a carbon-neutral operation by 2050. These two carbon goals will be used in the analysis.

ICAO supplied a list of fuels that are eligible to CORSIA requirements; thus, these fuels can be used to lower the total emissions that are subject to payments in the compulsory CORSIA carbon mitigation scheme. Besides that, fuels need to get an ASTM certification to prove technological readiness. A third requirement is not to use ”first-generation” fuels, of which the feedstocks interfere with food production and have limited carbon mitigation power (e.g. palm oil).

Conceptual model

The conceptual model is an adapted version of the CO_2 emissions forecasting method from the Air Transport Action Group. The ATAG-method is developed to measure the effects of (1) traffic forecasts, (2) fleet fuel burn forecasts, (3) effects of technology and operations, (4) effects of alternative fuels, and (5) effects of emission reductions from other sectors (Market-Based Measures). The output should meet the carbon goal. If not, some steps need additional interventions, such as SAF offtake quantities. This process is called backcasting.

The conceptual model in Figure 3 uses these steps, but some extra dimensions are added. The carbon reduction scenarios (goals) are determined after step 3, and via backcasting steps 4 and 5 follow to fill the carbon gap. The initial order is shown with intermittent grey arrows, the new order with double black arrows.

The effects of SAF and the effects of Market-Based Measures both have sub-processes. In the first, a selection of SAF alternatives is added into the analysis. After determining the cumulative production of these SAF alternatives, the price development can be calculated. After calculating SAF quantities needed to reach goals, the NPV can be determined.

In the latter, cost reductions of the compulsory CORSIA and EU-ETS carbon schemes are added (due to less fossil fuel use), and the addition voluntary carbon credit costs if SAF can't close the carbon gap. This leads to a total NPV.

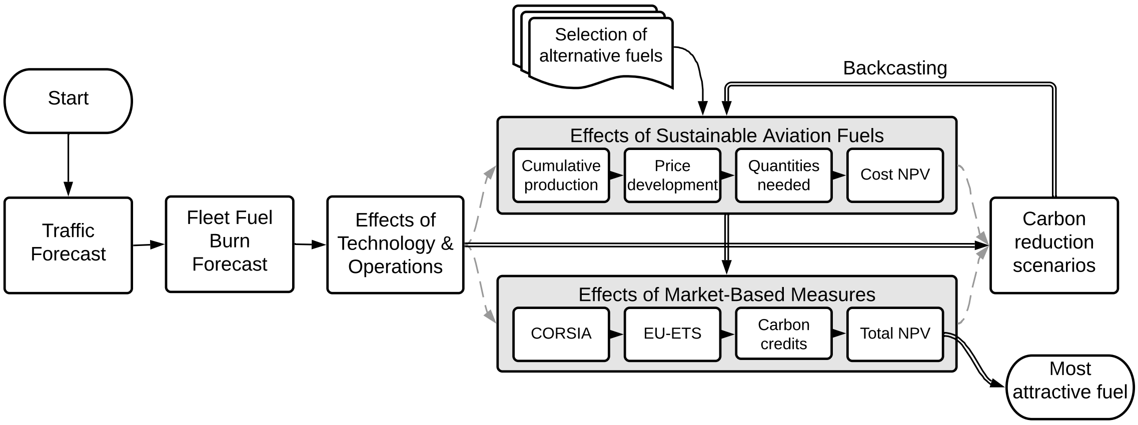

Figure 3: Conceptual Model

Traffic and CO2 forecast

The conceptual model is applied in Microsoft Excel and starts with TUI demand data from 2019 (79 million Revenue Passenger Kilometre and 5.3 million metric tonnes of $\mathrm{CO_2}$). Compound Annual Growth Rates are used from 2023 (COVID-recovery year equal to 2019), resulting in 181 million RPK in 2050. A ”Business as Usual” scenario gives 12 Mt $\mathrm{CO_2}$ in 2050. Considering the efficiency improvements of technology and operations, the expected $\mathrm{CO_2}$ emissions in 2050 would be 8.1 Mt.

Two carbon reduction scenarios are calculated to reach the two selected goals. The 50% reduction scenario requires a maximum of 2.11 Mt of $\mathrm{CO_2}$ in 2050. Starting in 2023 with 1% reduction requires a 17.3% annual growth factor in carbon mitigation. The net-zero scenario will lead to no emissions in 2050. This requires an 18.6% annual growth factor.

Fuel analysis

HEFA fuels (hydroprocessed esters and fatty acids) have the largest cumulative production in the coming 10 years. This is due to the maturity of the HEFA production process. Current total renewable fuel production is 5 million tonnes, reaching 13 Mt in 2025. Using cumulative production of SAF alternatives and their Minimum Selling Price (MSP) in the experience curve method gives future price projections. A technology-specific Process Ratio PR_i of 1 for HEFA fuels (due to maturity) and 0.9 for all other fuels have been used. Therefore, HEFA fuels have a constant price over time. One of the outstanding alternatives is FT-SPK (Fischer-Tropsch) made from Municipal Solid Waste, starting at 1729 USD/ton in 2020 and ending at 980 USD/ton in 2030.

Considering the different carbon reduction per SAF alternative, all fuels require another offtake quantity to close the carbon gap. Using these quantities and price projections lead to expected fuel costs. The costs of Market-Based Measures (voluntary and compulsory carbon schemes) are added, leading to a total Net Present Value.

Results

The most attractive SAF alternative in a social perspective is the fuel with the most carbon reduction potential. Within the second-generation fuels, the FT-SPK process with Municipal Solid Waste is the most promising alternative with more than 300 million tonnes of $\mathrm{CO_2}$ reduction potential per year. This SAF alternative is also most cost-efficient in a business perspective. To reach the 50% reduction scenario, the company needs to invest 695 million USD (Net Present Value). For the net-zero scenario, an investment of 875 million USD is required.

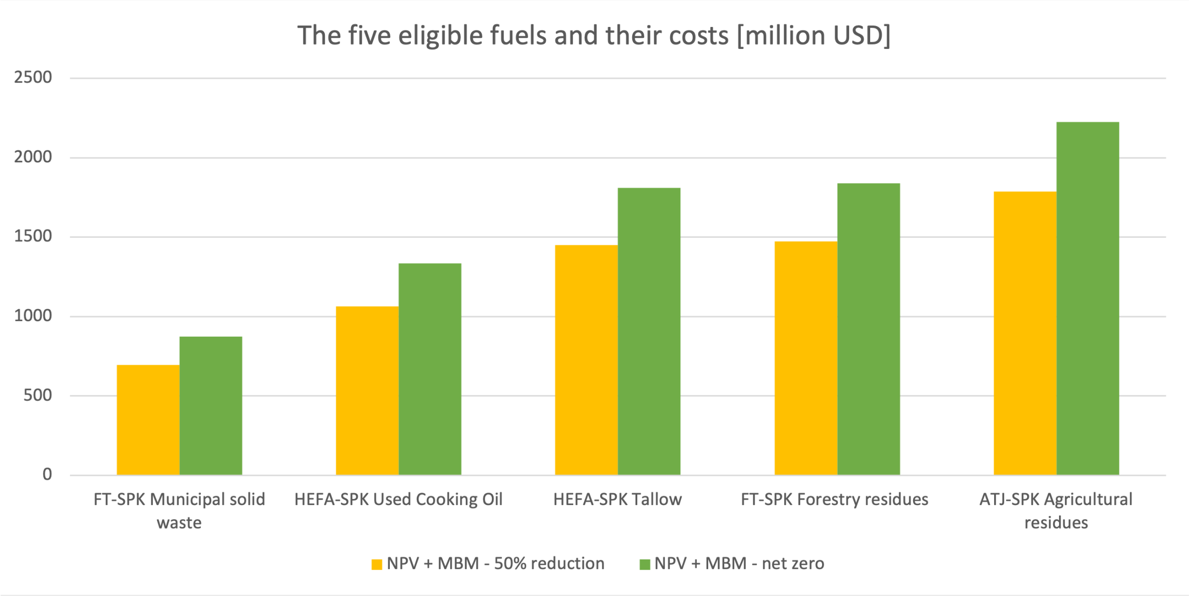

Figure 4: The resulting fuels that could be implemented in TUI Aviation operations

Conclusion and recommendations

This research aimed to find potential attractive SAF alternatives in a social and business perspective. With a literature review, it was determined that the aviation industry generally strives toward two goals; a 50% reduction of $\mathrm{CO_2}$ in 2050 compared to 2005, and a net-zero $\mathrm{CO_2}$ scenario in 2050. The demand forecast led to an increase from 79 million RPK in 2019 to 181 million RPK in 2050, which equals 5.3 and 12.1 million tonnes of $\mathrm{CO_2}$ respectively. Including the external effects of technology and operations resulted in 8.1 million tonnes in 2050. To fill the gap to meet the goals, SAF implementation was needed. After determining future production quantities, related selling prices, and selection by sustainability criteria of SAF alternatives, 5 out of 22 alternatives were potential to implement. After taking account extra costs due to economic measures, the FT-SPK fuel from Municipal Solid Waste scored best with a Net Present Value of 875 million USD for the net-zero scenario.

The main recommendations for further research are to include a fossil fuel price development tool (now set at a fixed price), to do more research into the Minimum Selling Price of SAF alternatives (large differences between sources), and to improve the cumulative production overview of these fuels. Other fuels that are not yet certified (such as Power-to-Liquid) could be added in the model later. And scientific research into the effects of contrails on global warming is limited, and therefore not included in this research.

Preface

Dear reader,

Thank you for being interested in sustainable aviation. Climate change is a global problem with an urge to solve quickly. As most people may know, commercial aviation is a large emitter of CO_2 emissions, and there are limited available possibilities to solve this in the short term. In my opinion, the aviation industry is there to stay, because people will keep the urge to explore the world during their holidays or to see business relations in real person instead of via digital meetings. However, it would be nice to travel without having to care about harming the environment.

This thesis explores the possibilities to introduce Sustainable Aviation Fuels (SAF) into the airline business. There are numerous SAF alternatives in the market or development. Still, it is difficult to determine which alternative would suit an airline company best in terms of carbon mitigation and cost. This research can hopefully help in the decision-making process of making commercial aviation more sustainable.

When I started at TUI Aviation in Rijswijk in February 2020, no one within the company expected that COVID-19 would impact the aviation industry and the world in general. Therefore, I would like to give my gratitude to all people in the TUI community. Even as an intern, I felt involved in all the crisis management surrounding this pandemic, partly because of the management that kept updating and reassuring all employees. Special thanks to Aviation Sustainability manager Tom Sutherland. Due to furloughed colleagues as a result of COVID-19, a larger workload wasn't a convenient situation for any of us, but Tom always tried to support me when necessary.

When we all started working from home, I finished my co-working duties at TUI Aviation (EU-ETS and CORSIA emissions reporting) and started drafting my thesis proposal. I could say that the decline in air traffic in spring 2020 was equal to the decrease in my motivation of starting with my thesis. Toward the summer season, aviation slowly began to recover, and so did the work on my thesis. But luckily, the second wave of COVID-19 infections in autumn 2020 did not hit me in terms of motivation, as it did with the decline in air traffic again. I started learning how to motivate myself while working from home, and with success.

Therefore, I would like to thank my daily supervisors at the TU Delft, Jan Anne Annema and Mark Duinkerken. As time progressed and my motivation increased, I started updating Jan Anne and Mark regularly. Their quick responses with feedback gave me even more motivation to continue doing this research. I also would like to thank Bert van Wee, the chairman of the committee. He gave valuable insights and feedback during the meetings.

Finally, I would like to thank my family, especially my parents and my girlfriend Loes. You discovered me struggling with the working from home situation and guided me to stick to my planning and update my supervisors regularly. Without that, the period without motivation could have been longer.

There is nothing more to me than to thank you, the reader, for being interested this research. Sustainability is essential to save our planet, so it is all the more crucial if as many people as possible know the sustainable possibilities within aviation!

Koen van Bentem
Delft, February 2021

About TU Delft

Top education and research are at the heart of the oldest and largest technical university in the Netherlands. Our 8 faculties offer 16 bachelor's and more than 30 master's programmes. Our more than 25,000 students and 6,000 employees share a fascination for science, design and technology. Our common mission: impact for a better society.

`https://www.tudelft.nl/en/about-tu-delft/`

About MSc TIL

The MSc programme in Transport, Infrastructure and Logistics (TIL) is a two-year comprehensive programme that provides graduates with a comprehensive view of the field of transport, infrastructure and logistics. TIL graduates know how to design new road, rail, air and water transportation services for passengers and/or freight; to efficiently manage transportation networks; and to design and control complex supply chains. These skills are invaluable for the design, development and maintenance of cost-effective, efficient systems for moving passengers and freight. TIL graduates are able to make appropriate decisions for clients, employers and society, because they understand the complex decision-making processes during infrastructure development and planning.

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About TUI Group

TUI Group is the world's number one integrated tourism group operating in around 180 destinations worldwide. The company is domiciled in Germany. The TUI Group's shares are listed in the FTSE 100 index, the leading index of the London Stock Exchange and in the German open market. In financial year 2018, the TUI Group recorded turnover of €19.5bn and an operating result of €1.147bn. The Group employs 70,000 people in more than 100 countries. TUI offers its more than 27 million customers comprehensive services from a single source. It covers the entire tourism value chain under one roof. This includes five European tour operator airlines from the UK, Germany, Sweden, the Netherlands and Belgium with 150 modern aircraft including more than 25 long-haul aircraft. The majority of the latter consists of the most-recent Boeing 787 Dreamliner. Furthermore, the Group comprises of around 380 own hotels and resorts and a fleet of 17 cruise ships. TUI features leading tour operator brands and more than 2,200 travel agencies. Global responsibility for sustainable economic, ecological and social activity is a key feature of our corporate culture. TUI Care Foundation supports the positive impacts of tourism. It initiates projects creating opportunities for the next generation and contributing to a positive development of the holiday destinations.

`https://www.tuigroup.com/`

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Acronyms

AR	Agricultural Residues
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet
BAU	Business As Usual
bbls	barrels (equivalent to 159 litres)
CAF	Conventional Aviation Fuel
CAGR	Compound Annual Growth Rate
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent
dLUC	Direct Land Use Change
EEA	European Economic Area
EU	European Union
EU RED	European Union Renewable Energy Directive
EU-ETS	European Union Emission Trading Scheme
FR	Forestry Residues
FT	Fischer-Tropsch
GHG	Greenhouse Gas
HEFA	Hydroprocessed Esters and Fatty Acids
HFS	Hydroprocessed Fermented Sugars
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
iLUC	Indirect Land Use Change
kg	kilogram
l	liter (equivalent to 0.2642 USG)
LCA	Life Cycle Assessment
LSf	Life cycle emissions factor for a CORSIA Eligible fuel

LUC	Land Use Change
MBM	Market Based Measures
MJ	Mega joule (a measure of energy content)
MSP	Minimum selling price
MSW	Municipal Solid Waste
Mt	Megaton (equivalent to 10^6 metric tons or 10^9 kg)
NFPO	Non-Food Plant Oil
NPV	Net Present Value
RPK	Revenue Passenger Kilometer
SAF	Sustainable Aviation Fuels
SDG	UN Sustainable Development Goals
SIP	Synthetic Iso-paraffin
SPK	Synthesized Paraffinic Kerosene
UCO	Used Cooking Oil
USG	US gallons (equivalent to 3.7850 l)

1

Introduction

1.1. Background

It seems like only yesterday that sustainability was the single most important issue to be addressed by the aviation industry. The flight shaming movement started in Sweden by a teenager named Greta Thunberg [16], had gained international traction and caused a harsh light on aviation. The European nitrogen legislation has held the Netherlands in its grip since summer 2019, whereby aviation is not unharmed [99]. It started to convince corporations and individuals to rethink their air travel necessity and explore options like online conferences or other travel modes. The global aviation community, which achieved much already in eco-initiatives, including more fuel and emissions efficient aircraft, Sustainable Aviation Fuels, and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) scheme led by the International Civil Aviation Organization (ICAO) [49], was suddenly on the defence.

Since the COVID-19 pandemic, many people worldwide were forced to be in lock-down, which grounded much of the global passenger aircraft fleet. Some people say that with the global airline industry in survival mode sustainability and eco-goals need to be reset, especially if governments support their airlines to prevent them from collapsing [132]. Others say that the pandemic highlights the importance of living within earth constraints and needs. People are commenting on extreme reductions in pollution, since large portions of the world's population are confined to home, off the road or out of the air.

Recently, KLM Royal Dutch Airlines has been offered state aid to survive the COVID-crisis, but the Dutch government had set additional requirements before making this available [44]. The government requires KLM to bring back Carbon dioxide (CO2) emissions from international aviation in 2030 back to 2005 levels, and the emissions per passenger kilometre must be 50% lower than in 2005. Besides that, a 14% blending percentage of Sustainable Aviation Fuel must be achieved in 2030, among other conditions. To accomplish that, KLM will participate in the first SAF factory in the Netherlands.

1.2. Project context

World aviation fuel demand reached 5 million barrels (equivalent to 159 litres) (bbls) per day in 2014, which ensures aviation being the second major consumer of oil [40]. The total oil demand share of aviation in the transportation sector is 11.2% [83].

Commercial aviation is responsible for 2.6% of global CO_2 emissions, while the sector is growing at 5% per annum [115]. This growth can also be seen in Figure 1.2. The International Civil Aviation Organization expects that annual aviation emissions would grow by more than 300% by 2050 without additional measures [50].

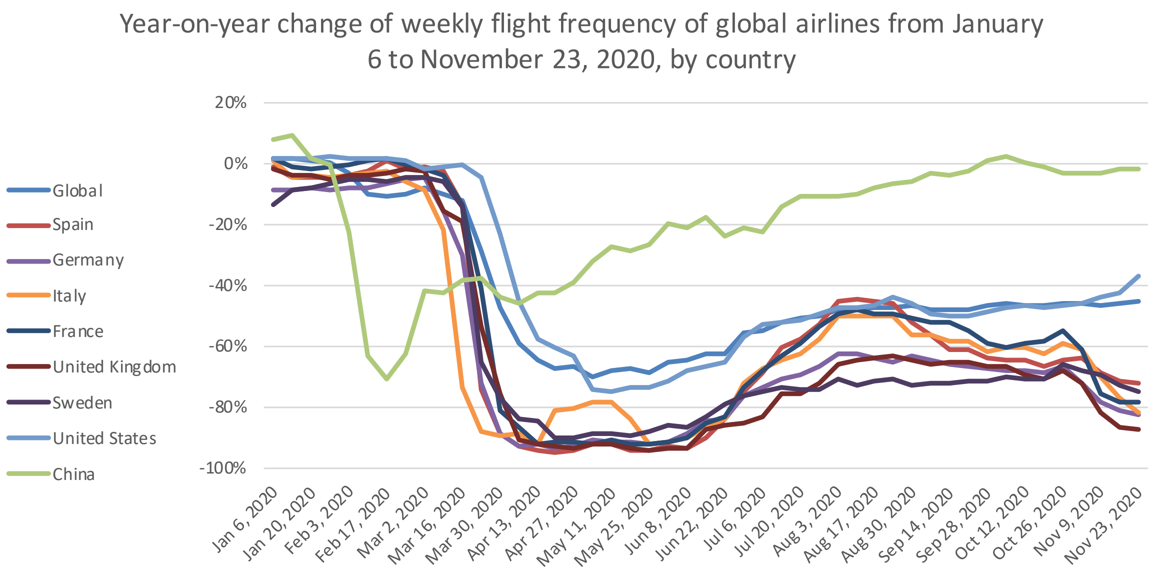


Figure 1.1: The impact of COVID-19 on commercial aviation. Data retrieved from Mazareanu [82]

One of the potential solutions to make commercial aviation greener is to introduce *Sustainable Aviation Fuel*, which is made from non-fossil feedstock. The use of SAF would reduce greenhouse effects, reduce fossil oil dependency, improve air quality and create new job opportunities [88]. In a scenario where 100% of the fuel consumption would be SAF in 2050, there would only be a 63% reduction in emissions [50], due to emissions during production. Scaling up the use of SAF would require large capital investments in production infrastructure, and substantial policy support is necessary.

Staples et al. [115] note that a full replacement of fossil-based jet fuel with sustainable aviation fuel in 2050 may result in an absolute increase in greenhouse gas emissions in the aviation industry compared to 2005. In this paper, the projected fuel demand increase in 2050 is estimated to be higher than the projected emissions reduction by introducing SAF, which causes this absolute increase in emissions. This means that further emissions reduction could be needed to reach goals, for example with the use of CO_2 offsets from other sectors.

Dietrich et al. [27] state that multiple energy sources or feedstocks can be used to produce SAF, which require different synthesis technologies, and these all have their own cost and emission structure. However, they don't give a full overview of cost and emission structures.

1.3. Research problem

Technological innovation would never be implemented without a cost-benefit analysis on the airline's side, as airlines' profit margins are generally low [28]. Airline companies eventually need to choose whether to invest in SAF and which SAF alternative would suit the airline operations best.

Previous research focused on the technological feasibility of SAF, or the urgency to implement SAF, but little research has been done into the economic feasibility of SAF. The only techno-economic analyses that can be found are papers that focus on either one or a limited number of SAF alternatives (e.g. Martinez-Hernandez et al. [80], Mustapha et al. [87], and Baral et al. [12]). Still, there is a research gap that compares all relevant SAF alternatives into one research. Numerous potential alternative fuels have been proposed, but an exact comparison of the possibilities and costs cannot be found in the public domain, yet. It could be that other airlines already did research in this subject, but confidentiality and competitive

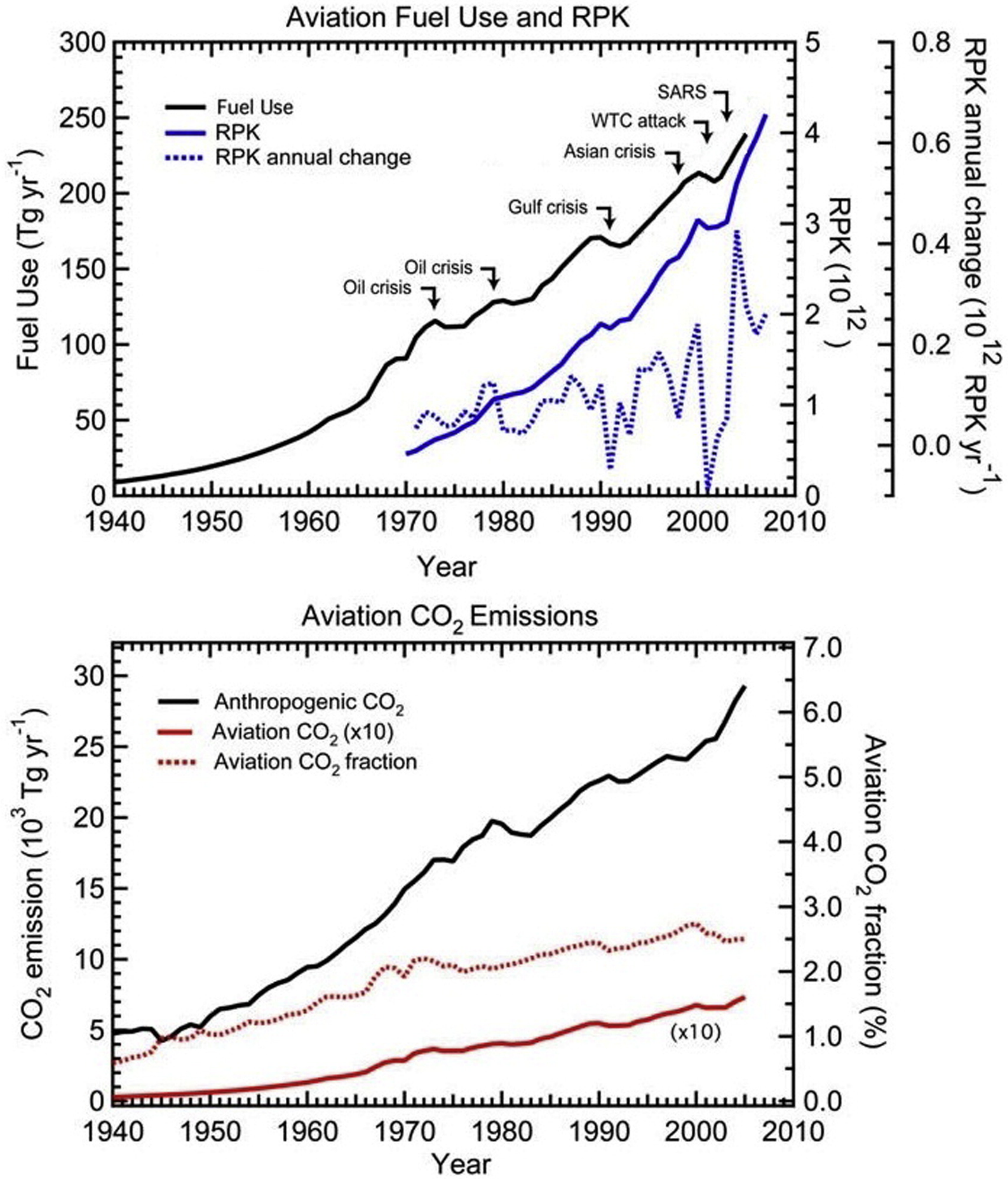


Figure 1.2: (Top) Aviation fuel usage (in Teragram = Mt), and the growth in air traffic in RPK. The impact of world events on aviation is shown. (Bottom) The CO_2 emissions caused by anthropogenic (human) activities, CO_2 emissions from aviation fuel burn (multiplied by 10 for readability), and the fraction of aviation in the total anthropogenic emissions. Adapted from Lee et al. [71]

advantages are reasons not to publish their results.

Besides that, no research has been found that states the increase of SAF production and how this would influence future prices of SAF alternatives. Combining these factors into one research would give a clear and complete view of the attractiveness of SAF alternatives for the aviation industry.

1.4. Research objective

This research aims to determine which Sustainable Aviation Fuels are most attractive in a social and business perspective. The most attractive fuel in a social perspective is the one that could ensure the largest carbon mitigation potential. The most attractive fuel in a business perspective is determined by delivering the Net Present Value of the investment needed for implementing each existing SAF alternative.

The research starts with a stakeholder analysis to determine the main policies and regulations regarding carbon mitigation in commercial aviation. With this information, a carbon goal can be determined. Next, it is required to know what SAF quantities need to be implemented. To be able to find those quantities, a traffic forecast is done. This determines future air traffic in the period 2020-2050. This traffic forecast is converted into CO_2 emissions, taking into account external factors that would reduce carbon emissions. The gap between this CO_2 emission forecast and the carbon goal needs to be filled by introducing SAF. Each of the SAF alternatives has its characteristics, like the production pathway (synthesis technology), energy feedstock, emissions reduction and future cost projection. These characteristics are taken into account in the Net Present Values of the required investment costs for implementing the SAF alternatives, leading to differences in attractiveness. The ultimate objective is to deliver a Net Present Value of the investment needed for each of the SAF alternatives separately (Total Cost of Ownership).

TUI Aviation

This research is done by doing a case study at TUI Aviation. Their role is to provide air traffic demand data and CO_2 data that are related to that demand, so that the model and the outcome of this research match reality as closely as possible. This may result in new scientific insights into the subject, and it could propose courses of action for TUI Aviation to limit carbon emissions.

The TUI Group is the world's largest tourism agency and operates 5 airlines in the United Kingdom, Germany, Belgium, the Netherlands and Sweden. These five airlines all have their own Air Operator Certificate in their respective country. These countries can have different government policies and regulations related to the introduction of SAF, which can affect the ultimate choice.

The outcome of this research will be a leading source in the development of a SAF implementation strategy within the TUI Group.

1.5. Research questions

To make sure the research is done well, the main research question is formulated that should be answered after the research has been performed:

> What are potential attractive SAF alternatives in a social and business perspective?

To answer the main research question, sub-questions are needed to support the research and collect the required information to answer the main research question.

1. What stakeholders in commercial aviation are involved and what are the regulations, policies and goals regarding SAF that they have set?

This stakeholder analysis is needed to determine which goals and regulations have been set by both international organisations and national governments to limit carbon emissions within commercial aviation. These answers can influence the total quantity of SAF needed to comply with these regulations, which will influence the total cost involved. Also, there will be a look into the carbon policies that other airlines have set to determine whether any carbon reduction plans for TUI Aviation align with competitors.

2. What is the current traffic forecast until 2050, taking the current COVID-19 crisis into account?

Before any carbon reduction plans can be made, it is needed to forecast the air traffic demand for the period 2020-2050. When a large traffic growth is forecasted, more carbon emissions need to be mitigated (and thus more SAF quantities are needed), compared to moderate or little growth.

3. What are the resulting emissions from the traffic forecast, taking the effects of technology and operations into account?

The traffic forecast will lead to an expected growth in carbon emissions (assuming a traffic growth in the last sub-question). Carbon efficiency KPIs will be used to determine the emissions toward 2050. External factors that could reduce the total carbon emissions (such as new aircraft technologies or improvement in Air Traffic Control) will be accounted for in this sub-question.

4. What is the advised timeline of carbon mitigation?

A timeline of carbon mitigation will be developed based on the expected growth in carbon emissions from sub-question 3 and the policies and regulations in sub-question 1. This timeline will state the advised carbon reduction per year (compared to the carbon emissions from sub-question 3) to reach certain goals or comply with certain regulations.

5. What SAF innovations are currently in development or on the market?

This sub-question is meant to provide an initial set of SAF alternatives that could be implemented by an airline.

6. What SAF innovations comply with selection criteria regarding technological feasibility, cost/benefit, stakeholder acceptability, and timescale of adoption?

The initial set of SAF alternatives will be analysed, and there will be determined what fuels will be used in an in-depth analysis. There will be tested whether fuels are technically ready to be implemented, whether stakeholders would accept the use of these fuels, and whether the selected fuels will be commercially available in the short term. The cost/benefit will be decided in the in-depth analysis.

7. What is the influence of Market-Based Measures in the attractiveness of SAF alternatives?

There are also other ways to reduce carbon emissions, for instance, by purchasing carbon credits from other organisations (that, i.e. plant trees or invest in clean energy). Besides that, there are obligatory carbon mitigation schemes for commercial aviation. The opportunities and costs of these market-based measures could influence the attractiveness of introducing SAF.

2

Methodology

This chapter will focus on the design of the thesis and research involved. By following this methodology in the following chapters, the research questions' answers will eventually be found. At first, the theoretical framework will be discussed in section 2.1, followed by the research strategy in section 2.2. The research methods needed to execute this research are mentioned after in section 2.3. These methods will be visualised in a research framework in section 2.4, followed by this research's scope in section 2.5. The interdisciplinarity (regarding the interdisciplinary Master TIL) can be found in section 2.6, and the relevance for society will be discussed in section 2.7. This chapter will conclude with a Thesis Layout in section 2.8.

2.1. Theoretical perspective

Two theoretical perspectives are essential for this research. Profit Maximisation will be discussed in subsection 2.1.1, and Environmental Corporate Social Responsibility is explained in subsection 2.1.2.

2.1.1. Profit Maximisation

Primeaux and Stieber [97] describe that profit maximisation can be mentioned in two perspectives; technical and behavioural. Technically, profit maximisation is the "set of conditions where the marginal revenue of the firm is equal to its marginal cost", where marginal revenue is decreasing, and marginal cost is increasing with increased production [97]. This means that a firm should continue production as long as the revenues per unit sold exceed the cost. At that point, the firm operates at the production level that guarantees a maximum profit. As can be seen in Figure 2.1, an increase of marginal costs from MC1 to MC2 leads to a lower production quantity. One way to avoid that is to improve marginal revenue (orange line), but that is impossible without setting a higher sale price. Another way to prevent a quantity reduction is to lower the marginal costs again, i.e. by economising on other expenses.

In a behavioural perspective, profit maximisation is described as "the act of producing the right kind and the right amount of goods and services the consumer wants at the lowest possible cost (within the legal and ethical mores of the community)" [97]. This means that businesses deliver goods and services, and these are the right "kind" if there is a demand for them.

This theoretical perspective is vital in this research because the introduction of SAF alternatives would lead to more marginal costs. The consequence is that the unit quantity will decrease (i.e. the number of passengers). One solution to prevent the quantity decrease is to increase marginal revenue and thus, the sales price. This isn't easy because customers

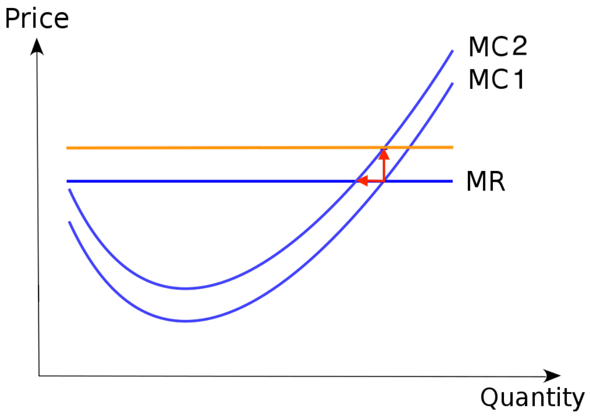


Figure 2.1: Marginal cost and revenue curve

are less willing to pay for more expensive flight tickets. Another solution is to lower the costs again by saving on other expenses. But in a highly competitive market, we can assume that cost reduction has been a primary point of attention already.

To conclude, profit maximisation is essential for the company's profitability, and an investment like the introduction of SAF is only possible by losing passengers, saving other costs, or increasing ticket prices. Therefore, the goal is to minimise the investment needed to introduce SAF, so the effect on the marginal cost will be as low as possible.

2.1.2. Market Forces and Environmental CSR

Lyon and Maxwell [79] describe that the growing attention to corporate environmental initiatives in the business press strongly suggests that market forces are increasingly powerful drivers of corporate environmental improvements.

The production and sale of environmentally friendly products is a growing business in all sectors. Arora and Gangopadhyay [9] were the first to give an economic explanation of this growth in green consumption. They applied a standard vertical product differentiation model to capture the consumer heterogeneity in willingness to pay for environmental products. In this situation, it is interesting for a company to increase its quality to reduce price competition with rivals. Bagnoli and Watts [10] showed that the level of competition in a market affects the amounts of environmental CSR companies undertake. If the market for less environmentally-friendly (brown) products is highly competitive, prices will be low, and fewer consumers will wish to buy environmentally-friendly (green) products. However, if the brown market loses market share, prices will rise, and consumers will more likely switch to the green products.

Not only the consumer market but also the investment and labour market are sensitive for companies with CSR [79]. Research showed that investors prefer investing in socially responsible companies, which increases the firm's value by attracting those customers. Employees want to feel good about the company they work for; thus, it is crucial to make environmental commitments aligned with these employees' environmental values. University graduates are also willing to accept substantially lower salaries from firms engaged in socially responsible activities. And if pollution abatement is cheap, the gains from labourmarket screening still outweigh the costs of abatement [79].

There are also supplyside forces that encourage firms to adopt a greener production. There are numerous examples of firms that increased their resource use efficiency while reducing costs and pollution at the same time [79]. However, marketdriven emission reductions will not be sufficient to achieve a social optimum. Therefore, politics and governmental regulations will remain needed to drive environmental improvement.

2.2. Research Strategy

To schematically show the methodology in this research, Figure 2.2 from Johannesson and Perjons [66] is used. They describe the function of research strategies and methods and how these are interrelated. A research strategy is defined as an overall plan for conducting research that will guide the researcher in planning, executing, and monitoring the research. Research methods will guide the research on a more detailed level; these define how research data is collected and analysed.

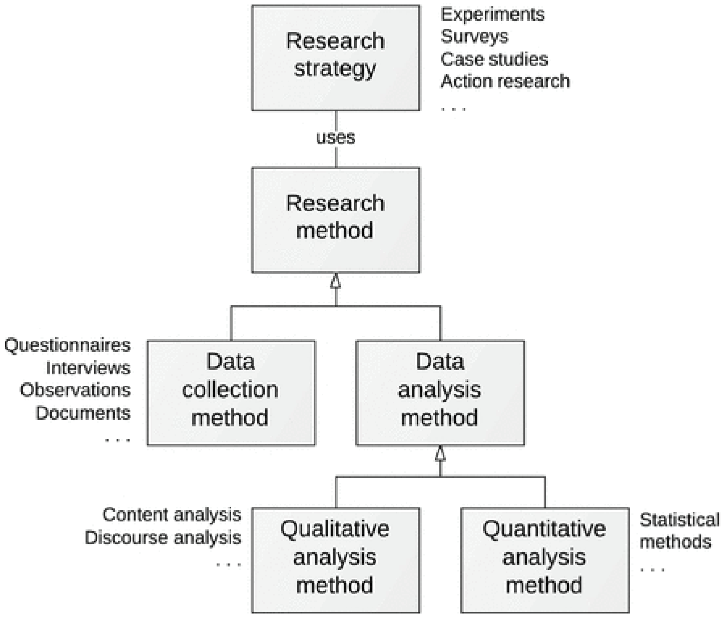


Figure 2.2: Research strategies and research methods. Adapted from Johannesson and Perjons [66]

Johannesson and Perjons [66] describe nine main research strategies; experiments, surveys, case studies, ethnography, grounded theory, action research, phenomenology, simulation, and mathematical and logical proof. The action research is most applicable to this research. It addresses practical problems that appear in real-world settings, which can, for instance, be used in organisational change.

Action research focuses on practicality (instead of laboratory experiments), change of local practice, and active practitioner participation. It contains a cyclical process with feedback loops (by introducing, evaluating and reflecting changes). Action research leads to the production of both action outcomes for local practice and research outcomes that contribute to the academic knowledge base. The main challenge of action research studies is to generalise results because they are mostly tied to local practice. There are five phases in the cyclical action research process [66]:

- Diagnosis: Investigate and analyse the problem.
- Planning: Plan actions that can improve the current situation.
- Intervention: Carry out the actions to improve the current situation.
- Evaluation: Evaluate the effects of the intervention to see whether the situation has improved.
- Reflection: Reflect on the research and its action and research outcomes, to decide whether a new cycle is needed.

The action research strategy is used in this research; by *diagnosing* the problem in commercial aviation (CO_2 emissions), *planning* to introduce different SAF alternatives, *intervening* with the introduction of these SAF alternatives in a model, *evaluating* whether these SAF alternatives result in a better situation, and *reflecting* what the main findings of these research are (the most attractive SAF alternative). If the outcomes of this research (CO_2 reduction) would not suffice the goals that will be set, the feedback loop can be used by introducing an extra cycle. In this cycle, more actions could be carried out to improve the current situation.

The research outcomes would contribute to the academic knowledge base, which are results and conclusions that have a general view on commercial aviation and the implementation of SAF. The action outcomes for local practice are results and conclusions that contribute to the active practitioner, TUI Aviation. Therefore, the addition of local practice (the TUI Aviation business) could be seen as a case study, which is also one of the nine main research strategies.

Another main research strategy that is implemented is simulation. Action research focuses on the intervention in real-life situations (thus implementing SAF and evaluating the effects). However, simulations are an imitation of the behaviour of a real-world process over time [66]. It can be used when it is expensive to use the real-world process, or when it is needed to perform analysis or to make predictions before the actions are carried out. Simulation is often used in strategic management.

2.3. Research methods

Research methods can be referred to as tools and describe the way how the analysis is performed. These research methods are needed to use the theory and data as input in the analysis to get to the results, and they support the execution of the research strategy.

The main research method is desk research. By reviewing literature and combining data from different sources, it is the ultimate goal to deliver a coherent story that contains an effective strategy to introduce SAF. The search engine used for finding literature is Google Scholar. The collected data will afterwards be applied to a case study within TUI Aviation.

2.3.1. Data Collection methods

Data collection is needed before any analysis can be done. Therefore, the following methods will be used to retrieve the data.

Traffic forecasting data

Quantitative traffic data is needed to start the analysis. Operational data of 2019 is retrieved from the TUI Aviation database and used to measure air traffic in 2019. General air traffic growth data is extracted from academic publications. Multiple papers focus on traffic forecasts, so a literature review is needed to ensure the information of different sources is compared and mind research gaps that could restrict data provision. Main search command used is ”aviation growth factor”.

Besides that, traffic forecast data and recovery analysis data regarding COVID-19 are needed. Although academic research did not publish many relevant papers yet, many industry experts already lighted their view on the recovery process. Therefore, newspaper articles will be mainly used to find estimated recovery years (pre-COVID-19 levels), to be found by the keywords ”aviation COVID recovery year”.

The traffic forecast will then be used as a baseline to determine the effects of Technology and Operations (such as newer, more fuel-efficient aircraft). These effects are also described in academic publications, so a literature review with different sources is needed to review these data’s reliability and usability.

Sustainable Aviation Fuels data

The second part of the analysis needs data about SAF alternatives. Before the effects of alternative fuels can be analysed, we need to know its effects. There are multiple forms of SAF in production or development; thus, it is essential to have a clear overview of the different characteristics. The fuels have different feedstocks and production processes. Besides that, production costs are needed to do estimate future price projections.

All information will be retrieved using a literature review. It is crucial to use multiple sources and review the data because different researchers may have used different scenarios. Although the characteristics of two fuels may be the same, the production costs could be different, because due to the production location, the feedstock costs are different. Main search commands used are ”sustainable aviation fuel techno-economic analysis” and ”sustainable aviation fuel minimum selling price”.

Stakeholder data

The theory chapter will end with a stakeholder analysis in sustainable aviation. This part is essential because an overview of carbon mitigation policies and goals is needed before a strategy can be created to hold these policies and goals. Besides that, there will be a look at the policies and goals of competing airlines. The primary importance is to focus on an international level, not only because commercial aviation is mainly a global business. The case study at TUI Aviation is related to five airlines based in different countries, with different regulations, policies and goals.

The information will be assembled using a literature review. Main keywords are ”aviation carbon goal”, ”sustainable aviation fuel quota”, ”aviation sustainable development goals”, and ”aviation carbon offsetting”.

2.3.2. Data Analysis methods

After data has been retrieved, this can be used as input for the data analysis. As the data is primarily quantitative, the analysis will also be quantitative.

CO2 emissions forecasting method

Air Transport Action Group [4] describes a research method that fits the goals of this research to determine future CO_2 emissions, which can be seen in Figure 2.3. This method is later referred to as the ATAG-method.

The first step of the method consists of economic modelling and traffic forecasting to determine future air traffic. Air Transport Action Group [4] includes the COVID-19 situation by indicating three main scenarios. Step 2 uses the aviation traffic forecast in Figure 2.3 as an input for a fuel burn forecasting process. Data of baseline fleet and operations are used to determine the CO_2 levels. Normally, the amount of fuel used is converted into CO_2 emissions by using the factor 3.16 kg CO_2 per kg Fuel. Step 3 is to include technology and operational improvements in the model. New aircraft can be more fuel-efficient, so the fuel use per RPK (and therefore the CO_2 per RPK) can decline by these improvements.

In step 4, the effects of alternative fuels are modelled. This step requires some assumptions that include the SAF implementation rate (leading to offtake quantities) and the life cycle emissions of those SAF alternatives. Lastly in step 5, the addition of emissions reductions from other sectors (including market-based-measures like CORSIA or European Union Emission Trading Scheme (EU-ETS)) are modelled.

The carbon goal is stated at the right of the model in Figure 2.3 [4]. The CO_2 forecasting process should meet the carbon goal after all steps described above are included. If not, some steps of the CO_2 forecasting process need additional interventions by adjusting the assumptions described above.

An increase of the SAF implementation rate leading to extra SAF offtake quantities in step 4, could ensure that the carbon goal will be met. Another possibility is to select another SAF alternative that has lower life cycle emissions. This ”feedback loop” intervention of going back to previous steps is called ”backcasting”. In this approach, the modelling assumptions are adjusted, such that the resulting carbon emissions forecast meets the carbon goal [4].

Dreborg [30] describes backcasting as an approach that involves working backwards from a particular desirable future end-point to the present, to be able to determine the physical feasibility of that future and to determine what policy measures would be required to reach that point. In this case study, it is first needed to determine the desirable end-point (i.e. carbon levels in 2050), before we model the addition of sustainable aviation fuels to reach that desirable end-point. Therefore, the ”Goal” in Figure 2.3 will be determined first in this research, after which the effects of alternative fuels will be backcasted.

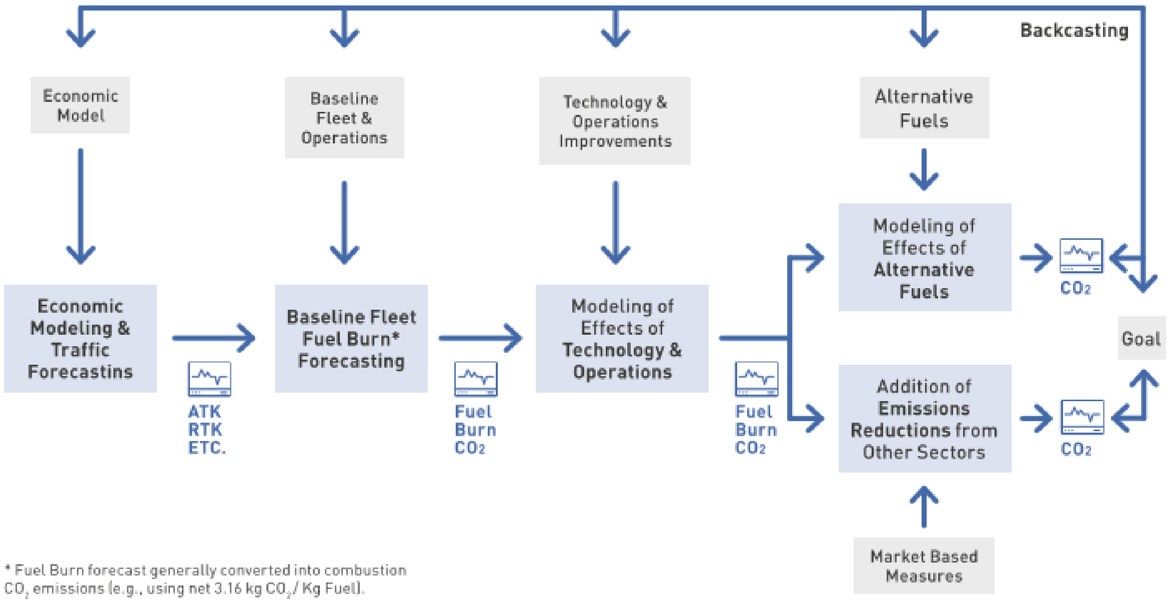


Figure 2.3: Method for forecasting CO_2 emissions. Adapted from Air Transport Action Group [4]

The CO_2 emissions forecasting method from ATAG gives a transparent process of CO_2 forecasting, but three main components are missing in this method. The components are described below.

Forecasting techniques

At first, economic modelling and traffic forecasting are done in a global aviation perspective. However, the research strategy is to use local practice (a case study with TUI Aviation data). Therefore, it would be better to use the traffic forecasting data described earlier. To be able to handle these data, forecasting techniques are needed.

The forecasting analysis will start with a qualitative technique to estimate the COVID-19 recovery year. After the literature review, an estimation is being made of the recovery process after COVID-19. By the unique character of this crisis, it is hard to estimate demand with a quantitative method. Expert opinions are arguably more valuable.

At the point of recovery (the moment at which the traffic forecast is equal to the period before the COVID-19 crisis), quantitative forecasting is more thrust-worthy. Whereas other researchers use global air traffic growth curves, this implies that fast-growing markets like

China and India are considered. Therefore, a time-series technique with trend will be used that takes TUI-specific trend values into account.

Experience curve price analysis

The ATAG-method doesn't indicate the kind of SAF that would be best to implement in a social or business perspective, and there is no possibility for comparison of SAF alternatives. Therefore, the second component added to the ATAG-method is the addition of a method that can calculate future SAF price projections.

It is important what the future production costs (or prices) are for the SAF alternatives. According to IATA [46], the trading market for SAF is opaque. There is no referenced market price for SAF like there is for other products like crude oil or Fossil Aviation Fuel. The experience curve method uses scaling and learning effects to determine future prices with increased production. Weiss et al. [134] used a methodology, including an experience curve approach suitable for this research.

Cost-Benefit Analysis

The ATAG-model includes the CO_2 emissions of the SAF alternatives, but not the associated costs. Therefore, the third component that is missing is the method to determine the most attractive SAF alternative, while taking into account the traffic forecast, CO_2 forecast, and SAF price forecast.

At first, the most attractive alternative in a social perspective will be determined. This is the largest carbon reduction potential, taking into account (potential) production levels. The most attractive alternative in a business perspective is the fuel with the lowest Net Present Value implementation costs for a 30 year period in a Cost-Benefit Analysis. These costs will include the costs associated with the SAF offtake quantities needed to reach carbon reduction goals, but also costs such as market-based measures and the decrease of fossil fuel costs.

2.4. Research Framework

In Figure 2.4, the research framework can be found. The first step is the literature review of specific concepts and principles in the Theory chapter. This is followed by the creation of a conceptual model, which translates the concepts and principles into model components.

In the computerised model, the data analysis methods have their place. These methods are described in section 2.3. The analysis will start with traffic forecasting techniques, followed by an analysis with the CO_2 emissions forecasting method. An experience curve price analysis will be executed to determine future prices of SAF. The output of these analyses will be used in the final analysis, where the SAF alternatives will be compared in a Cost-Benefit Analysis.

The finished computerised model will be verified and validated to ensure that the model works correctly and the output is reliable. After that, The Cost-Benefit Analysis output will be used in a sensitivity analysis by testing the input variables' sensitivity.

The output of the computerised model is the Net Present Value, resulting from the Cost-Benefit Analysis.

2.5. Scoping

This research will mainly focus on the case study within TUI Aviation while using industry-based data. Data from the commercial aviation sector (and the tourism sector to a lesser extend) will be used to do the analyses described above. TUI Aviation is both an airline and subsidiary to the world's largest tourism group.

To relate this scope to the research strategy in section 2.2, research outcomes that will contribute to the academic knowledge base will be based on commercial aviation in general.

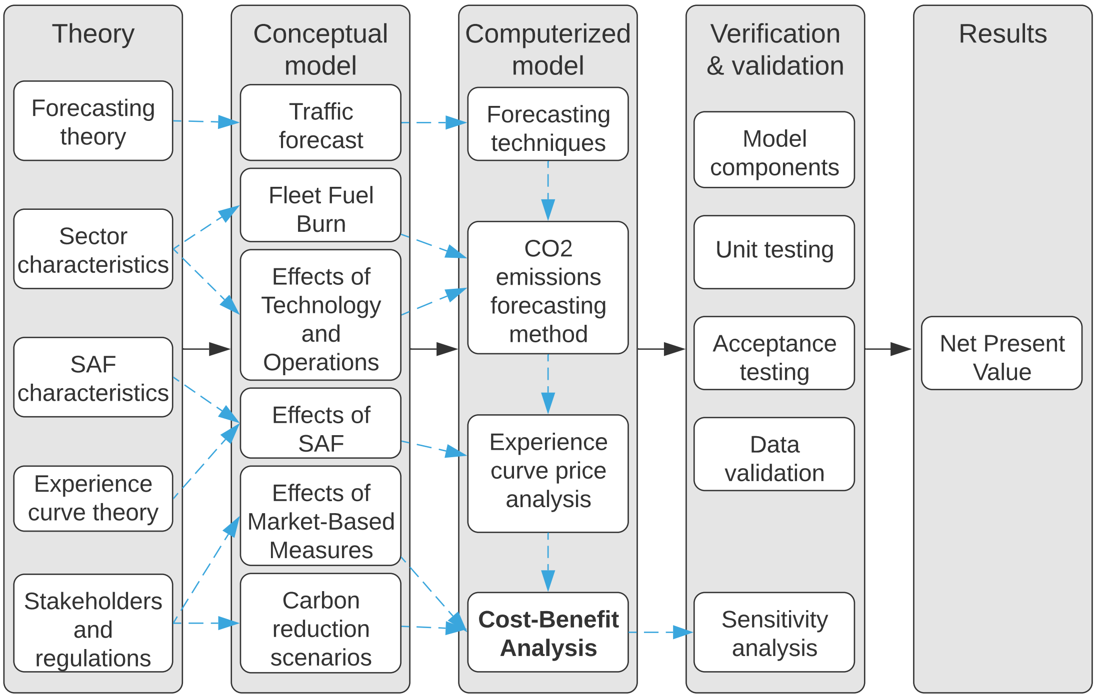


Figure 2.4: Research framework of this thesis

Action outcomes for local practice will contribute to the case study with TUI Aviation operational data.

The research is limited to the mitigation of CO_2 emissions; these are the emissions that have the most considerable impact on climate change [71]. Other emissions and climate effects have less scientific foundations, and can therefore be measured in a model less accurately.

The research will focus on four main carbon mitigation strategies. CO_2 levels could be reduced by improving technological efficiency (aircraft and engine technology), improvements in operational efficiency (aircraft operations and air traffic management), the introduction of Sustainable Aviation Fuels, and the inclusion of economic measures (or Market-Based Measures). Other potential CO_2 reduction possibilities are not known to impact overall CO_2 reduction significantly.

2.6. Interdisciplinarity

This thesis could be seen as interdisciplinary due to the combination of policy analysis, demand forecasting and cost-benefit analysis. The various topics within this thesis that require literature review are related to the faculty of Technology, Policy and Management. The introduction of SAF and the analysis for feasibility could have been a subject in the course ”Innovations in Transport & Logistics”. The link with Transport Engineering & Logistics can be found in the execution of forecasting analysis, which relates to the course ”Quantitative Methods for Logistics”. There is also a link with the course ”Airline Planning & Optimisation” at Aerospace Engineering faculty. To conclude, this research uses multiple theories, methods and tools which makes this project interdisciplinary.

2.7. Relevance for society

The introduction of SAF was already relevant and actual to ensure the greenhouse gas emissions caused by aviation will be mitigated. However, now it is more important than ever. The flight shame movement set the aviation industry in a harsh light. The decrease in air and noise pollution around airports during the COVID-19 pandemic gives governments and people the incentive to think about the future of air travel. Therefore, a solution is needed to make the aviation industry greener.

2.8. Thesis layout

In Figure 2.5, the visual representation of this thesis can be found. The main research question and sub-questions have been provided earlier, and these will be answered in the chapters that follow.

The following chapters are based on the methodology. In chapter 3, a literature review is included to set a theoretical framework, and initial data needed for the analysis will be collected. Therefore, some sub-questions will already be answered here. There will be a description of policies, regulations and goals (**sub-question 1**) and there will be an overview of SAF innovations (**sub-question 5**).

After that, a conceptual model will be developed in chapter 4. This model will describe the different steps in the analysis, and it will show the components that the computerised model needs to have. These steps and components are based on the theoretical concepts and principles explained in chapter 3.

In chapter 5, the conceptual model will be used to create a computerised model, which will be made in Microsoft Excel. This computerised model will be able to make calculations that are needed to answer the remaining sub-questions.

Before the computerised model's output can be used, it is needed to do verification and validation on the model in chapter 6. There will be checked whether the model works how it needs to and whether the outcomes match reality. A sensitivity analysis of input variables is part of this process.

This will be followed by an explanation of the results of the computerised model in chapter 7. Using tables and graphs will be able to provide the output of the computerised model visually. The output contains information that is need to answer **all remaining sub-questions** (except sub-questions 1 and 5). The output/results will be discussed in the conclusion of this research in chapter 8.

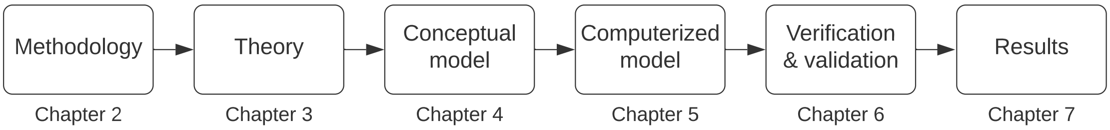


Figure 2.5: Summarising picture of this thesis

3

Theory and data collection

This chapter will focus on the theoretical foundation needed to execute this analysis. It also includes initial data collection found in literature that is required in further steps. Five main topics need to be discussed, which will be used in the analysis afterwards.

The chapter will start with a description of stakeholders, policies and regulations around this subject in section 3.1. After that, an explanation of forecasting theory and demand predictions can be found in section 3.2. This will be followed by aviation sector characteristics and the emissions caused by the sector in section 3.3. The opportunity to introduce SAF and its characteristics will be discussed in section 3.4. This chapter will be finalised with the experience curve theory in section 3.5, which will later be used to determine future price trends of SAF.

3.1. Stakeholders and regulations

Sustainable aviation is the goal for the entire industry, including airlines, governments and international organisations. These stakeholders can have different policies, regulations and goals regarding aviation sustainability, impacting the ultimate choice for the most attractive type of SAF. Therefore, policy analysis is needed.

3.1.1. International organisations

Multiple international organisations have set goals or regulations regarding sustainable aviation. They are explained below.

UN Sustainable Development Goals

In 2015, the United Nations General Assembly set 17 goals designed to be a ”blueprint to achieve a better and more sustainable future for all” [123]. The UN Sustainable Development Goals (SDG) are intended to be achieved by 2030.

For commercial aviation, two goals are most important. Goal number 7 states that energy needs to be clean and affordable. Although this goal mainly focuses on clean electricity, it also mentions energy in general. Besides that, alternative energy sources for aircraft, like electricity or hydrogen, fit within this goal. Goal 13 is to tackle climate change. According to United Nations Sustainable Development [123], 2019 was the second warmest year on record and CO_2 levels rose to new records. The UN indicates that COVID-19 ensures a temporary drop of about 6% due to travel bans and economic slowdowns, but this improvement is only temporary. The Paris Agreement supports the UN’s view, which aims to keep the global temperature rise well below 2 degrees Celsius above pre-industrial levels this century. The targets to reach these goals can be found in Appendix B.

Figure 3.1: Sustainable Development Goals

International Civil Aviation Organization

As discussed earlier, CORSIA is the carbon mitigation method developed by ICAO to ensure carbon-neutral growth from 2021. One of the measures that airline can make is to use SAF. However, not all SAF alternatives can be used [55]. Some principles and criteria indicate whether a fuel is eligible in the CORSIA scheme.

> *CORSIA sustainability criteria for CORSIA eligible fuels [55]*
>
> - *Principle: CORSIA eligible fuel should generate lower carbon emissions on a life cycle basis.*
>   - *Criterion 1: CORSIA eligible fuel shall achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.*
> - *Principle: CORSIA eligible fuel should not be made from biomass obtained from land with high carbon stock.*
>   - *Criterion 1: CORSIA eligible fuel shall not be made from biomass obtained from land converted after 1 January 2008 that was primary forest, wetlands, or peatlands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peatlands as these lands all have high carbon stocks.*
>   - *Criterion 2: In the event of land use conversion after 1 January 2008, as defined based on IPCC land categories, Direct Land Use Change (dLUC) emissions shall be calculated. If dLUC greenhouse gas emissions exceed the default Indirect Land Use Change (iLUC) value, the dLUC value shall replace the default iLUC value.*

van Velzen et al. [126] describe that CORSIA will cost around 15 USD/ton, although only the emissions that are above the baseline of 2019 emissions will be charged.

European Union Renewable Energy Directive

The EU-ETS system an emission trading scheme that requires CO_2 emitting companies to buy carbon allowances and is meant to reduce greenhouse gases. SAF can be used to minimise total carbon emissions and the ETS-allowances needed. However, not every SAF is applicable for the EU-ETS system.

The EU set up the European Union Renewable Energy Directive (EU RED) to define sustainability and the criteria toward fuels [34]. The EU RED is a mandate in the EU to ensure that 14% of the energy consumed in road and rail transport by 2030 will be renewable energy. Although the aviation and maritime sectors are not subject to this obligation, the EU RED sustainability criteria regarding fuels are adapted by EU-ETS. The sustainability criteria regarding SAF in the EU RED Recast are as follows:

- Greenhouse gas emissions from biofuels must be lower than from the fossil fuels they replace:
    - At least 50% for biofuels produced in installations older than 5 October 2015
    - At least 60% for installations after that date
    - At least 65% for installations starting operation after 2021.
- Land use change: raw materials for biofuels production cannot be sourced from land with high biodiversity or high carbon stock (such as primary and protected forests, highly biodiverse grassland, wetlands, and peat-lands)

EU-ETS costs are envisioned to be around 43 EUR/ton CO_2 in the long term, which equals to 50 USD/ton CO_2 [126].

3.1.2. National governments

Some national governments are setting up mandates to blend SAF into conventional jet fuel. Squadrin and Schmit [113] mention that the Nordic countries are at the forefront of SAF mandates, with Finland and Sweden striving for a 30% SAF blending mandate in 2030. Sweden wants to increase that mandate to 100% in 2045 [14]. France starts with a 1% quota in 2022, which will gradually increase to 5% in 2030 and 50% in 2050 [113], while Germany published a draft quota to start with 0.5% in 2025, increasing to 2% in 2030. Ministerie van IenW [84] imposes the use of 14% SAF in 2030 for the Netherlands, which increases to 100% in 2050. Norway started with a 0.5% fuel mandate in 2020 and is considering a 30% blend in 2030 [111], and in 2025 Spain will have a 2% SAF supply objective. The United Kingdom is investigating possibilities to introduce a mandate in 2025 [43].

These mandates, both decisions and considerations, are included in Table 3.1. The assumption is that considered mandates by governments will eventually be mandatory; thus, these are included too.

Table 3.1: Governmental mandates to blend SAF

Departure country	Fuel share	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2045	2050
Finland	0.7%											30.0%	30.0%	30.0%
France	2.5%			1.0%	1.0%	1.0%	2.0%	2.0%	2.0%	2.0%	2.0%	5.0%	5.0%	50.0%
Germany	8.7%						0.5%	0.5%	0.5%	1.0%	1.0%	2.0%	2.0%	2.0%
Netherlands	7.1%											14.0%	14.0%	100.0%
Norway	0.2%	0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	8.0%	12.0%	17.0%	23.0%	30.0%	30.0%	30.0%
Spain	15.1%						2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Sweden	2.3%		1.0%	2.0%	3.0%	4.0%	5.0%	8.0%	12.0%	17.0%	23.0%	30.0%	100.0%	100.0%
United States	1.2%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Total	37.6%	0.1%	0.1%	0.1%	0.2%	0.2%	0.6%	0.6%	0.7%	0.9%	1.1%	2.6%	4.2%	11.4%

3.1.3. Voluntary offsetting programs

There are also international organisations that offer voluntary offsetting [89]. This is also known as ”climate compensation”. Companies or individuals could choose to offset the emissions they make in their business or personal life. ICAO [58] stated some voluntary carbon offsetting organisations with the right certifications and invest in, e.g. clean energy and planting trees, which cost approximately 10 USD per tonne of CO_2.

The main disadvantage of these voluntary carbon offsets is that they don't mitigate CO_2 immediately. It takes a long time for trees to grow and sequester the planned amount of CO_2 [89]. Therefore, voluntary offsetting programs are seen as short-term solutions. SAF is a solution for the medium and long term because it prevents the extraction of extra carbon by pumping crude oil from geological formations beneath the earth's surface.

3.1.4. Other airlines

Since the Paris Agreement and the set up of the UN Sustainable Development Goals, most airlines have been formulating their carbon reduction goals. International Air Transport Association (IATA) set up an industry-wide goal to achieve a 50% reduction of carbon emissions in 2050 compared to 2005.

In Table C.1 (Appendix C), the carbon goals of some of the largest airlines in the world can be found. The environmental reports of the respective airlines are used to retrieve the information. Some airlines did not state any specific carbon reduction goals, and others stick to the IATA guidelines. The Oneworld alliance (with British Airways, American Airlines, Qatar Airways, among others) set the goal to have net-zero emissions in 2050 [93].

In Table C.2, an overview of airlines' current SAF consumption can be found. The information is extracted from environmental reports of the respective airlines. A percentage is calculated that defines the share of SAF with CAF. Some airlines advertise with absolute SAF offtaking numbers (”we use 10 million gallons of SAF this year”), which arguably has a large value in marketing and environmental image. However, recalculating these numbers to Mt and comparing them with the CAF consumption, results in only minor shares.

3.1.5. TUI Group

TUI Group formulated its group-wide sustainability strategy named ”Better Holidays, Better World” in 2015 for the next five years. At the time of writing, the new sustainability strategy for 2020-2025 is in development. As can be seen in Figure 3.2, the four main pillars within the sustainability strategy are linked with the UN SDG, which have been discussed earlier.

In the first pillar named ”Step Lightly”, TUI Group wants to reduce the environmental impact of holidays, contributing to the 7th and 13th SDG. This is the pillar that is important for the emissions strategy of TUI Aviation. The goal is to operate Europe's most carbon-efficient airlines and reduce their operations' carbon intensity by 10% by 2020 [118], as measured in terms of TUI Airlines' average grams of carbon emitted per revenue passenger kilometre (gCO_2/RPK).

TUI Aviation accounts for over 80% of the carbon footprint of TUI Group; therefore, the focus is to reduce these airlines' climate impact. TUI airlines' relative carbon emissions were 65.2 gram per RPK (gCO_2/RPK) in the Fiscal Year 2018-19. The company uses the most fuel-efficient aircraft in the market, like the Boeing 787 Dreamliner and the Boeing 737 MAX, which means future emissions improvements need to be achieved by other means.

Other measures to minimise carbon emissions are [120]:

- Process optimisation, e. g. single-engine taxiing in and out, acceleration altitude reduction, drag reduction, mass and balance optimisation and wind uplinks.
- Weight reduction, e. g. introduction of carbon brakes and water uplift optimisation.
- Flight planning optimisation, e. g. alternate distance optimisation, statistical taxi fuel, minimum fuel optimisation, and an optimised cleaning schedule.
- Constant refinement of the fuel management system to improve fuel analysis and pilot communication, track savings and identify further opportunities.

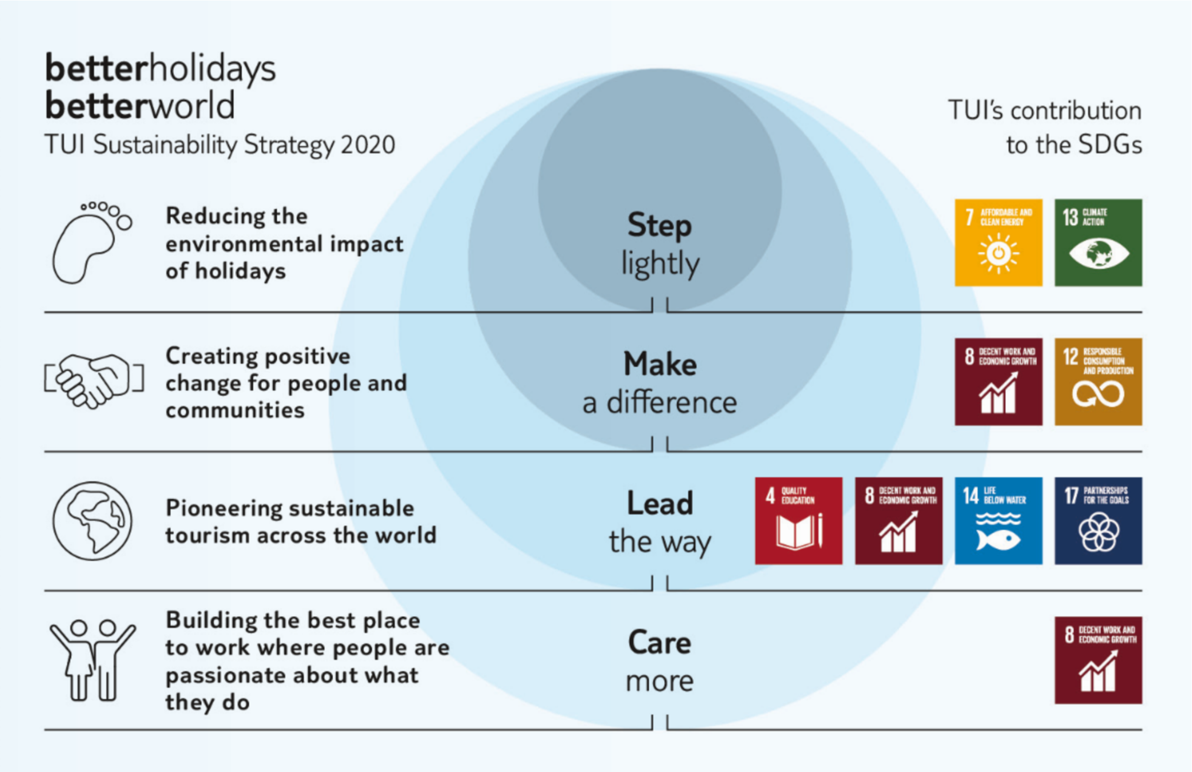


Figure 3.2: TUI Group's Sustainable Development Goals. Adapted from TUI Group [119].

3.2. Forecasting theory

Forecasting could be defined as the art of predicting the occurrence of events before these actually take place [8]. Forecasts provide information to policymakers and planners to make decisions. The author emphasises two main approaches to make forecasts. The first is using numerical methods and can be used to analyse and generate data. The latter is the intuition, experience, and practical knowledge of experts in the field. Combining these two approaches would deliver the most satisfactory forecasts.

3.2.1. Quantitative methods

The time-series method involves analysing linear and exponential trends, cyclical (seasonality) changes, and combined linear/exponential and cyclical changes. In Figure 3.3 from Iacus et al. [45], you can see the trend in global air traffic passengers (increasing passenger numbers over the years), while the seasonality can be seen in the variability during each year; in the northern hemisphere summer, the volume of passengers is larger than in the winter. If there is regularity in the data, a forecast can be made by observing the nature of this regularity and the frequency distribution of the associated set of deviations [8]. However, simple regularity is rare, so more sophisticated forecasting techniques have to be applied.

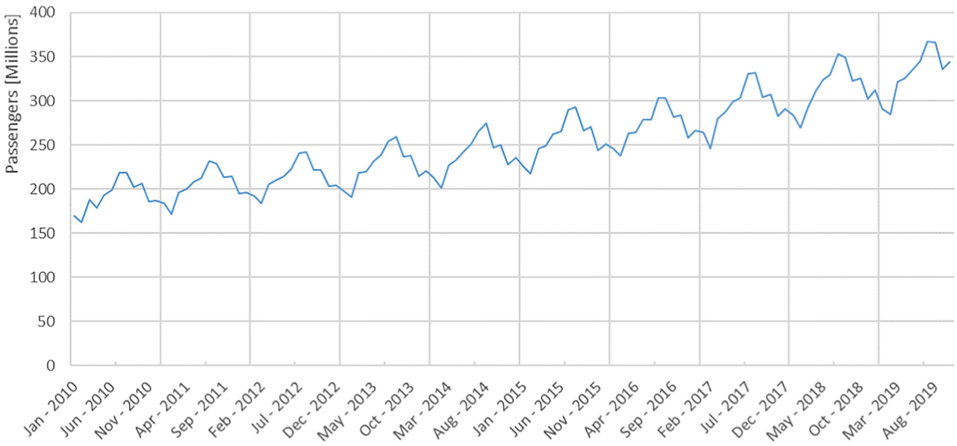


Figure 3.3: Aggregated volume of global air traffic passengers from January 2010 to October 2019. Adapted from Iacus et al. [45]

Two main techniques are the moving average technique and the exponential smoothing technique. The moving average technique adds up the sum of the last n observations and divides them by n, so that with each next forecast the last observation is dropped and the most recent one is added. With exponential smoothing, a weighted moving average is used, where the heaviest weights are given to the most recent observations. Older data are discounted more heavily.

$$F_t = \alpha * D_{t-1} + (1 - \alpha) * F_{t-1} \tag{3.1}$$

Where F_0 is the forecast for the next time period, α is the parameter that takes a value between 0 and 1, D_{t-1} is the most recent observation, and F_{t-1} is the last forecast. To use seasonality within this technique, it is possible to isolate the effects of the trend cycle, seasonality, and irregularities. The trend-cycle can be used in the exponential smoothing technique.

$$A = O/S = CI \tag{3.2}$$

Where A is the seasonally adjusted data, that is computed month by month by dividing the original data O by the seasonality factor of that month S. This equals the trend cycle C times irregularity I.

However, these techniques mainly work if you can work with observations. For short-term forecasts, this could be possible (such as demand forecasting for the next week/month/year). Still, it is impossible to use these techniques to calculate forecasts until 2050 due to a lack of observations. Besides that, the usage of seasonality is not necessary for long-term forecasting, as the demand and emissions per year will be used toward 2050.

3.2.2. Growth Rates

To tackle the problem described above, it is better to use trend extrapolation. Future growth rates are needed that can be applied from a baseline year. For example, Lee et al. [71] notes that annual passenger traffic growth was 5.3% a year between 2000 and 2007. Janić [62] gives a growth rate of 5.4%. However, these growth rates have a global perspective, which would not apply to a TUI Aviation case study.

ICAO [53] uses RPK in their calculations and notes that the Compound Annual Growth Rate (CAGR) for 2015-2035 is 4.3% per year, while it is 4.1% per year for 2015-2045. Most of this growth can be found in Asia, while the market in Europe is more stabilised. They mention that for Intra Europe flights, only 2.6% CAGR is expected. An overview with a selection of region pairs can be found in Figure 3.4.

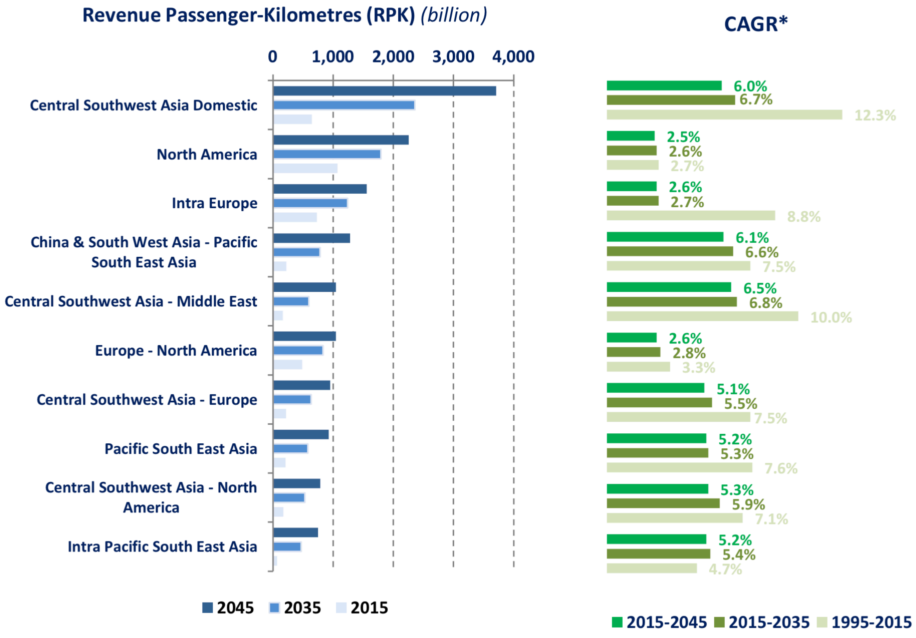


Figure 3.4: Compound Annual Growth Rates per RPK. Adapted from ICAO [53]

3.2.3. Qualitative methods

Before working with the growth rates discussed above, it is needed to determine the baseline year. COVID-19 has impacted the aviation industry, thus using the CAGR with a baseline year before the COVID crisis would give false results. Therefore, qualitative methods are used to determine the correct baseline year.

Archer [8] named quantitative and qualitative approaches that can be used for forecasting. The latter depends on individual experts or groups of people's accumulated experience to predict the likely outcome of events. Qualitative methods are mostly used when data are insufficient or inadequate for processing, or where numerical analysis is inappropriate due to changes of a previously inexperienced dimension.

Multiple techniques can be used [8]. The first is a detailed survey that can be sent to researchers and companies to determine future demand. However, supply constraints within companies could lead to other answers, in which the unsatisfied demand is not taken account for. Another example is the use of an expert panel. In gatherings, experts reach an agreed forecast after they used debates and interchange of ideas. This consensus approach is widely used in the business world. A third technique is a morphological analysis, where the goal is to structure existing information in an orderly manner and identify the probable outcome of events. Another technique is the Delphi method, where the goal is to reach a group opinion while each individual participating is not influenced by the personalities or rhetoric of other participants. They answer a questionnaire anonymously, and the answers are collected by directing staff, which combine the answers and give feedback on the group opinions at each stage.

Although these options won't be suitable for this thesis, experts' knowledge can still be used. By searching through literature and news articles, an estimation of the best baseline year can be given. This baseline (2020 or later) will have the same demand as 2019. Therefore, demand-data from 2019 can be used in the estimated baseline year, from which the trend extrapolation with growth rates can start.

3.2.4. The influence of COVID-19 on the air transport forecast

Some researchers already gave some insight into the air transport industry's recovery process during and after the COVID-19 pandemic. Abu-Rayash and Dincer [1] listed the recovery process of recent other pandemics, as can be seen in Figure 3.5. The SARS pandemic in 2003 was the most severe recent epidemic and reduced air transport demand by 35% at the height of that crisis. The researchers concluded that air transport demand remained below Business As Usual (BAU) for 6 months after the start of the SARS pandemic. This resulted in an annual decrease of revenue by 8%. Thus, they suggested that the COVID-19 crisis would see the same recovery process.

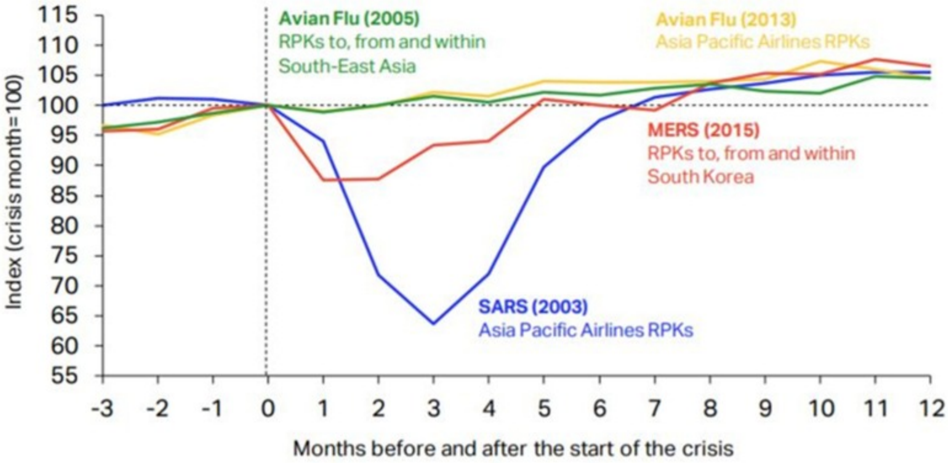
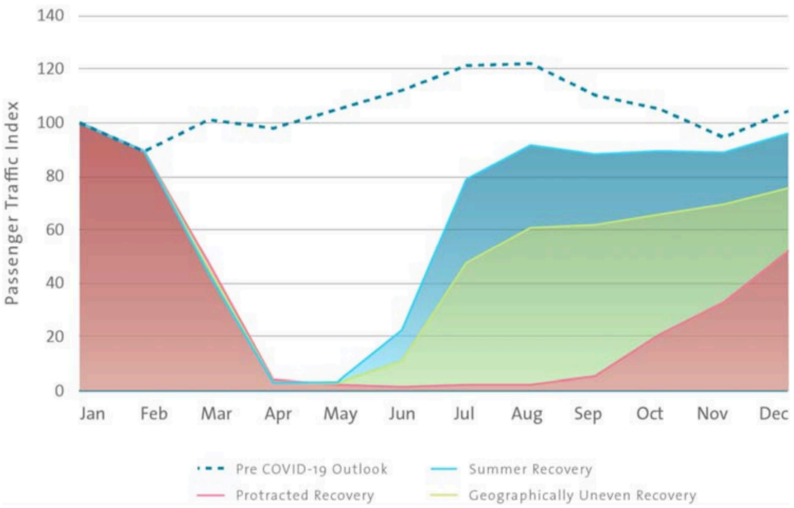


Figure 3.5: The influence of previous pandemics on commercial aviation. Adapted from Abu-Rayash and Dincer [1]

However, Abu-Rayash and Dincer [1] did not take the severity of the COVID-19 crisis into account. For instance, Haryanto [41] noted that global airline passenger revenue would decrease by 55% in 2020 compared to 2019. This gives a large contrast with the SARS crisis in 2003, where only 8% of the revenue was lost. Gössling [39] explains that 58% of the air transport demand comes from international tourism, which has come to a complete stand-still in spring 2020 due to closed borders.

InterVISTAS Consulting and NACO [61] did research into the recovery, too. They note that once the pandemic is under control, uncertainty will subside quickly. Households will then raise their spending back to more typical levels, taking into account the money saved because planned spending in 2020 did not occur. Related to the pandemic control profile, they formulated three scenarios. Note that these scenarios were developed at the end of March 2020. The "Protracted Recovery" scenario would fit best now, because of the flare-up of the outbreak at the time of writing (October 2020), with multiple (European) countries going into a new lockdown. Recovery would not occur until 2022 or 2023, according to this scenario.



Summer Recovery

Global restrictions start to be lifted in June.

Rapid build-up, but quite a lot of summer traffic lost.

Closing on full recovery by late 2020/early 2021.

37% of passenger traffic lost.

Protracted Recovery

Global restrictions remain in place for extended period due to continued flare ups.

Restrictions not lifted until September – traffic at 50% of normal levels by December.

71% of passenger traffic lost – full recovery not until 2022 or 2023.

Geographically Uneven Recovery

Some parts of the world control the outbreak and others do not (e.g., airports in North America have service within North America, but not to Europe and Asia).

50% of passenger traffic lost – full recovery by mid to late 2021.

Figure 3.6: Scenarios for Traffic Recovery in 2020. Adapted from InterVISTAS Consulting and NACO [61]

There are multiple other scenarios in development or debate. Smit et al. [110] developed nine different economic scenarios, some of which implying severe damage, while others are more optimistic. Ali [6] uses these scenarios to predict air travel recovery. Reasoning that the 9/11 crisis recovery took 3 years and the 2008 financial crisis 2 years, the researcher expects the air travel industry to need a five-year recovery cycle to come to pre-COVID levels. Plane manufacturer Airbus has warned that the aviation sector could take three to five years to recover [67].

Airlines are publishing their forecasts, too. Delta Air Lines CEO Ed Bastian expects air travel not to rebound to pre-pandemic levels for another three years [124]. Deutsche Bank expects Air France-KLM to be recovered in 2024 [74], with a W-shaped recovery path. Lufthansa takes 2024 into account, too [76], just as Emirates [104]. International Airlines Group (IAG), with British Airways and Iberia, states that it will take at least until 2023 before air transport demand is fully recovered [75].

However, TUI Netherlands managing director Arjan Kers states that the demand for air tourism (package holidays) would be recovered to 80% in 2021, with a full recovery in 2022

[77]. More recently, TUI Group CEO Fritz Joussen stated that around 80% of the flights would be operated during the 2021 summer season, with a full recovery expected in 2022 due to the roll-out of the COVID vaccine [91]. The main reason for this is that TUI is not dependent on the recovery of business traffic, whereas the legacy carriers named above do. Business travellers (temporarily) replace travels with online meetings, while a digital solution can not replace a holiday experience. Leisure airline Jet2 (also handling package holidays) expects the demand to largely recover in one year [105]. Low-cost carriers also heavily rely on tourism traffic. EasyJet had seen demand recover quicker than the earlier expectation of 2024 [106], while Wizz Air targets a full recovery in one year [107].

Dzambazovski and Metodijeski [33] studied the effects of COVID-19 on tourism in North Macedonia. In a scenario where pandemic would end by the end of 2020, they expect international tourism levels from 2019 to be back between 2025 and 2027, depending on the effectiveness of the economic response.

3.3. Sector characteristics

This section is used to fully understand the impact of aviation on the environment and the potential measures of the aviation sector to limit carbon emissions. The first will be discussed in subsection 3.3.1, the latter in subsection 3.3.2.

3.3.1. Current environmental impact of commercial aviation

According to Black [15] (TU Delft Library), the aviation sector has significant impacts on communities, consumers and employees. Although the consumer/employee impacts are manageable, communities' impacts have received less attention but are more serious.

Table 3.2 [15] gives the primary impacts that are discussed in literature. The two major problems are noise and emissions, which both have a significant impact on communities. Therefore, current aviation is not a sustainable transport mode [15]. The book section suggests that a clean alternative fuel could solve many of these problems. Until then, the aircraft sector will likely not move toward long-term sustainability in a meaningful way.

Table 3.2: Environmental impacts of aviation. Adapted from Black [15].

Nature of the impact	Impacted party or area
Deep vain thrombosis	Passengers
Airborne disease spread (e.g., tuberculosis)	Passengers
Cosmic radiation exposure	Crew
Aircraft noise pollution	Communities and airport personnel
Emissions - nitrogen oxides	Communities
Emissions - carbon oxides	Communities
Emissions - non methane volatile organic compounds	Communities

Climate change is one of the main challenges in the world. With the Paris agreement in 2015, countries agreed to keep global warming below 2°C above pre-industrial levels to protect our planet [29]. However, a difference between a 1.5°C and 2°C rise will significantly impact local weather conditions, like higher maximum temperatures and more extreme rainfall. Therefore, the goal needs to be to stay well under the 2°C.

Lee et al. [71] give a clear overview of the effects of aircraft emissions, which can be seen in Figure 3.7. These emissions can lead to climate change, which contains changes in temperature, a rising sea level, a decrease in ice and snow cover, and precipitation. These changes create impacts on human activities and ecosystems, which will ultimately lead to societal damages.

According to Noh et al. [90], CO_2 is the most important Greenhouse Gas (GHG) emitted by aircraft. Commercial aviation is responsible for 2.6% of global CO_2 emissions, while the sector is growing at 5% per annum [115]. The International Civil Aviation Organization expects that annual aviation emissions would grow by more than 300% by 2050 without additional measures [50]. The growth has substantial benefits, such as better world connectivity, but there is a major downside to this growth.

The aviation industry (led by IATA) set the goal to reduce the net emissions from aviation by 50% by 2050 compared to 2005 [94].

Environmental impact by contrails

Carbon dioxide is not the only emission that harms the environment. According to Warshay et al. [131], sulphur dioxide, nitrous oxides, particulate matter, and water vapour contrails are other harmful consequences of aircraft propulsion. The latter has the largest influence on global warming, although there is a lot of scientific uncertainty in the exact effects of contrails. The effects of contrails can also be seen on the right-hand side of Figure 3.7.

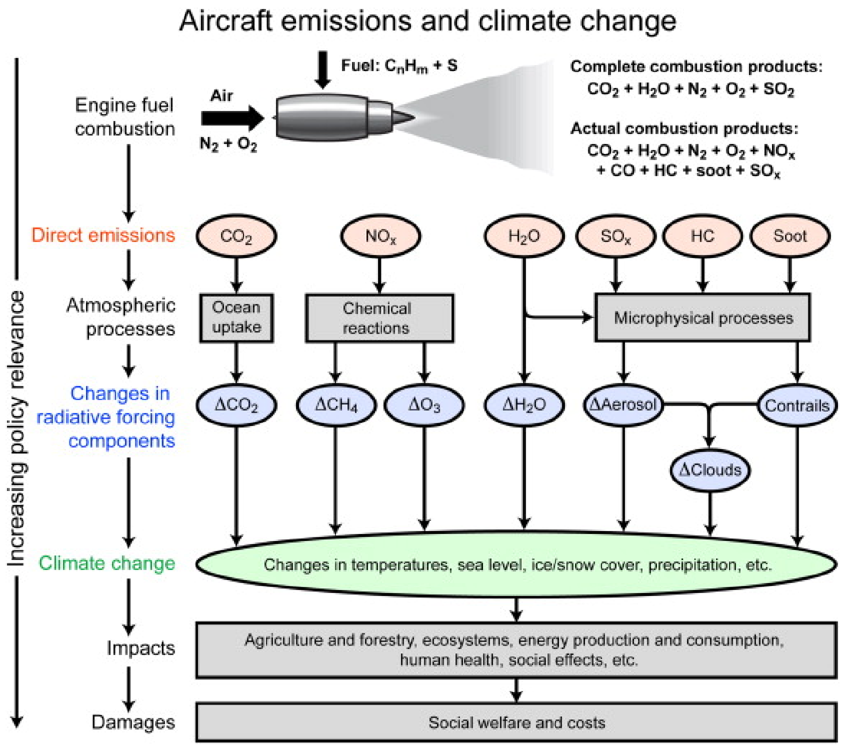


Figure 3.7: Scheme showing the emissions from aviation operations, and the resulting climate change, impacts and damages. Adapted from Lee et al. [71]

According to Turgut and Rosen [121], one of the main products of combustion in an aircraft engine is H_2O. Due to the high combustion temperatures, it is exhausted as water vapour. It mixes with ambient air and increases the relative humidity. The vapour turns into ice crystals when the ambient air temperature is sufficiently low and water saturation is reached, creating contrails (condensation trails), which are the visible trails behind aircraft [121]. According to Burkhardt et al. [17], soot exhaust (particulate matter) from aircraft engines ensure that water saturation is surpassed earlier, therefore high soot exhaust will lead to more contrails.

The resulting cirrus clouds can lead to extra radiative forcing, which results in global warming. If contrails are included in the environmental impact of aviation, commercial aviation is estimated to be responsible for 4.9% of all radiative forcing [71], although considerable uncertainty is involved. De Jong et al. [25] note that contrails increase the radiative forcing by a factor 2-5, compared to the impact of only CO_2 emissions.

However, Warshay et al. [131] note that low-carbon drop-in biofuels do not significantly change the combustion process or the mix of exhaust gases, including contrails. Hileman and Stratton [42] mention that contrails and contrail-cirrus formation are not changed by the use of synthetic paraffinic kerosene (SPK), compared to fossil fuel. Moore et al. [85] argue that HEFA biofuels could result in more contrails due to an increase in hydrogen content of the fuel, despite the expected lower particulate matter emissions (soot). Caiazzo et al. [18] expect that the introduction of alternative fuels will result in 8% more contrails due to the higher water emission index, despite the 67% to 75% reduction in aircraft soot emissions. Due to a different ice crystal size, the effects of alternative fuels on radiative forcing could be between -13% and +5%.

Yilmaz et al. [136] mention that liquid hydrogen as a fuel (a planned long-term replacement for fossil fuel) emits 2.5 times more water vapour mass than kerosene, although no CO_2 is emitted by using hydrogen.

3.3.2. Carbon mitigation measures

As shown in Figure 3.8, the expected aviation emissions would triple toward 2050 without additional measures. Some of the carbon reduction could be realised by technology, operations and infrastructure measures (fleet replacement, use of larger aircraft, increased density seating inside aircraft, improvements in Air Traffic Control and navigation procedures; according to Noh et al. [90]). However, this won't be enough to reach the goals set by the aviation industry. Economic measures (like carbon mitigation schemes; the red plane in Figure 3.8) are only meant as a short-term solution. Therefore, Sustainable Aviation Fuels are needed to reach the goals in the industry.

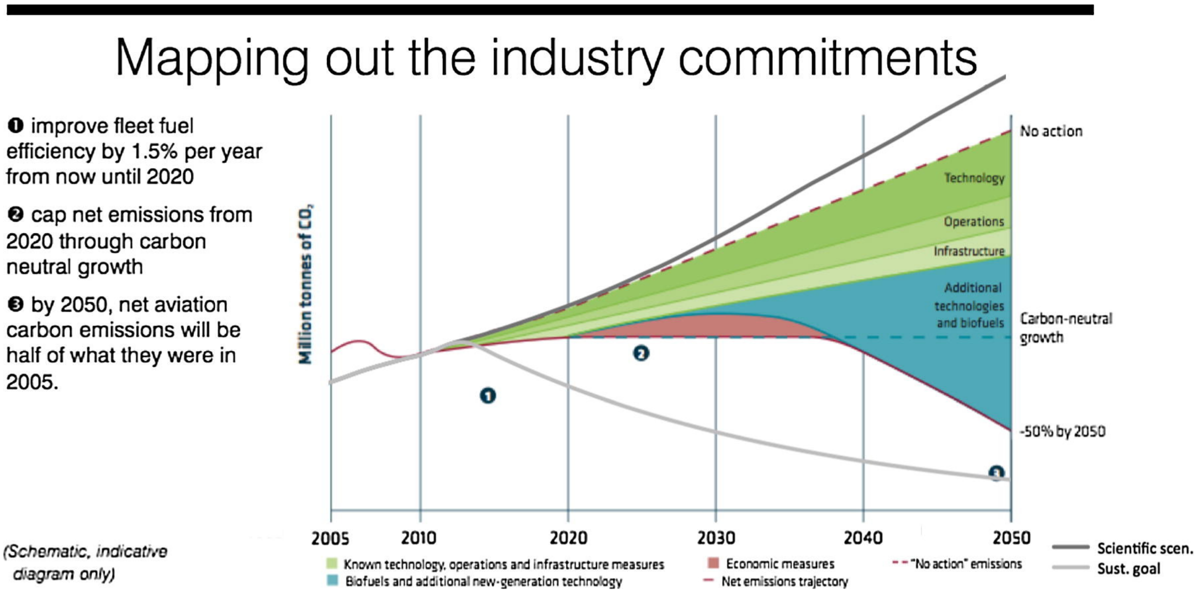


Figure 3.8: Long term targets for international aviation CO_2 emissions. Adapted from Peeters et al. [96]

There are different forms of carbon mitigation measures. Sgouridis et al. [103] describe that CO_2 reduction in commercial aviation could be achieved through five key levers. Technological efficiency improvements, operational efficiency improvements, market-based measures, and the use of SAF can mitigate the carbon emission from commercial aviation. A fifth lever is the demand shift; travellers' mode choice behaviour change, or the demand is reduced by the availability of non-travel alternatives like virtual meetings.

The last lever is not taken account for in this research, because TUI Aviation mainly transports tourists to destinations in Southern Europe and beyond. These destinations are practically impossible to reach by other modes, such as long-distance trains. The lack of business travellers will also exclude the reasoning of non-travel alternatives like virtual meetings.

The model in Figure 3.9 from Sgouridis et al. [103] complements this theory. It describes the three main stakeholders' behaviours in the aviation industry; passengers, airlines, and aircraft manufacturers. The most important aspects of this model for this research are the red variables, which are the levers discussed above. Aircraft manufacturers can ensure better technology efficiency, which leads to less fuel consumption and CO_2 emissions. Operational efficiencies have the same effects on fuel consumption and emissions. Carbon price (market-based measures) give an effective fuel price, which influences the overall fuel consumption due to increasing costs. Biofuels are directly related to CO_2 emissions, assuming they don't influence total fuel consumption, but they influence the total CO_2 emissions. Demand shift is also part of this model, but out of scope for this research.

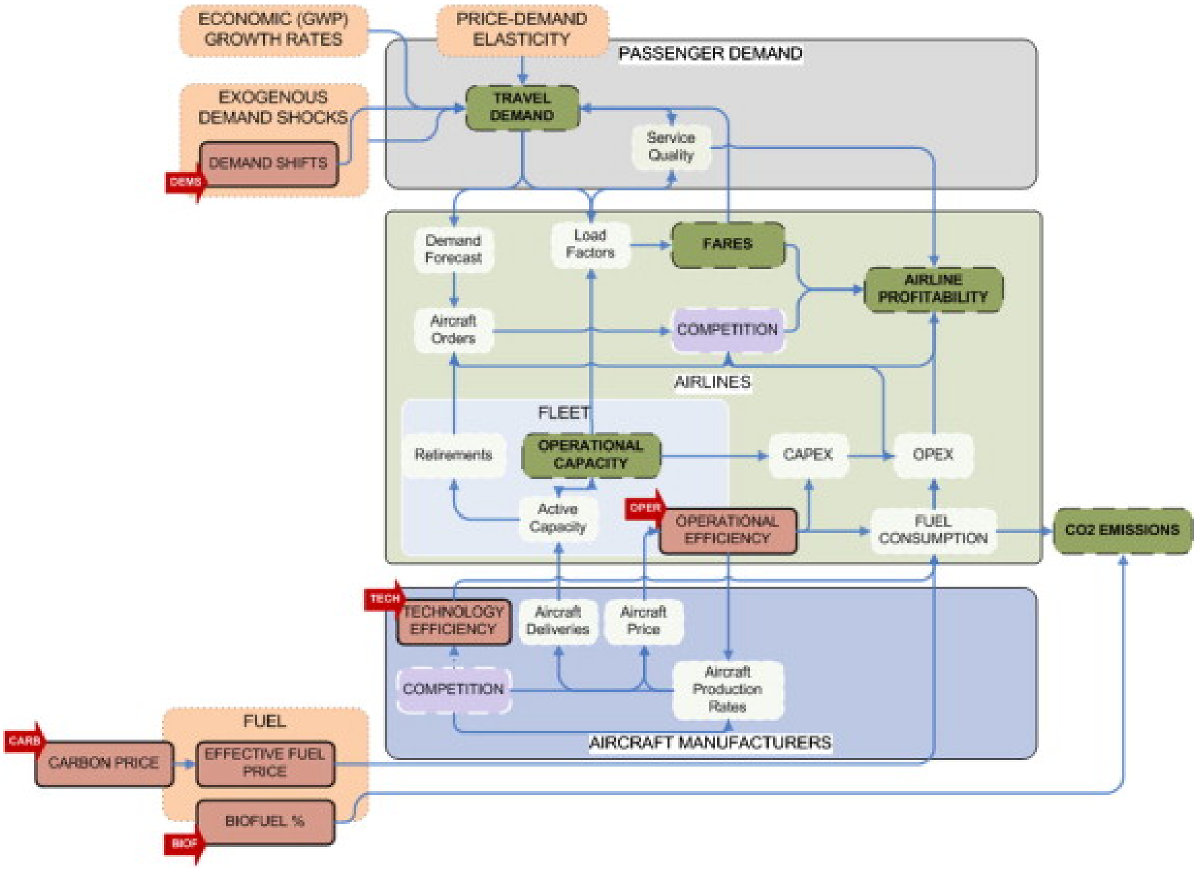


Figure 3.9: The Global Airline Industry Dynamics model. Adapted from Sgouridis et al. [103]

Technological efficiency improvements

The technological efficiency is related to a set of measures related to aircraft performance [103], and are the main responsibility of the aircraft manufacturer. This includes improved engine design, improved aerodynamics, improved wings, or reduced aircraft empty weight. These measures lead to less fuel consumption, which is favourable for the emissions of the particular aircraft. Engine efficiency improvements reached 1.5% per year, while aerodynamic improvements are 0.4% per year [103].

These improvements will typically evolve over a longer time period because aircraft are capital-intensive assets and fly for a longer time. For example, an airline can decide to replace an aircraft after a 20 year lifetime. The efficiency improvements of that particular aircraft are 0% during its lifetime, while a replacement aircraft will be 31.9% more efficient ($(1 - 0.015 - 0.004)^{20} = 0.681$). However, this step-wise descending trend will evolve in a smoother trend line if a whole fleet is involved. Therefore, the average efficiency improvements per year can be used in a fleet perspective.

However, newer research doesn't verify the percentages above. Zaporozhets et al. [137] indicate that 1.29% to 1.37% per year of technological efficiency improvements would be feasible toward 2050. EASA [34] indicates that the advanced technology scenario assumes a 1.16% improvement per year. Although older, Morris et al. [86] refers to only 1% improvement per annum.

Compared to other airlines, TUI Aviation already has one of the most carbon-efficient fleets globally, with the Boeing 787 Dreamliner and the Boeing 737 MAX. To make sure not to overestimate the CO_2 that would be mitigated in the future by aircraft replacement, 1% will be used in the analysis.

Operational efficiency improvements

To improve operational efficiency, changes are needed in the airline and air traffic control operations. Where the technology efficiency comes from the aircraft manufacturer, the operational efficiency can be influenced by the user. Infrastructure efficiency improvements are related to airport and air traffic infrastructure, and these are generally included in operational efficiency improvement numbers.

Some examples are optimised flight operations, such as fuel optimised climb/flight/descent paths, reduced cruise speeds, optimum altitudes, and reduced delays by Air Traffic Control [103]. Another operational efficiency improvement is aircraft weight reduction. While the aircraft empty weight is the manufacturer's responsibility (and thus a technological efficiency), the operating weight is the user's responsibility. This can be achieved by reducing fuel ferrying practices (taking more fuel than necessary because it is more expensive at the destination) or limiting the number and weight of baggage. Other minor improvements are the reduction of food and/or packaging weight. The last main improvement is optimising ground operations, such as single-engine taxiing, minimised queuing, and the use of tow-tugs instead of engine power for taxiing.

Sgouridis et al. [103] indicates that system-wide scale operational efficiency improvements of 12% could be achieved. Zaporozhets et al. [137] estimates a 6% to 9% reduction, while Air Transport Action Group [4] comes with 6%. Therefore, the minimum is chosen to avoid overestimation of carbon mitigation.

Market-based measures

Another key lever is economic measures, such as carbon pricing. A Market Based Measures (MBM) can be used as a mechanism to increase the effective price of fuel. This ensures a reduction in fuel demand through the price-demand elasticity relationship [103].

CORSIA is a global scheme developed by ICAO to ensure carbon-neutral growth from 2021 onward [49]. Any increase in carbon emissions from international flights above the baseline comes with a cost; airlines have to pay to offset these. The rules are strict, only certified projects (i.e. in reforestation) are allowed for carbon compensation. Both 2019 and 2020 should have been baseline years for airlines to determine their current emissions in international aviation. However, the average of these two baseline years would have been significantly lower due to the decline in air traffic due to COVID-19 [117]. Therefore, ICAO decided in June 2020 to only include 2019 as the baseline year.

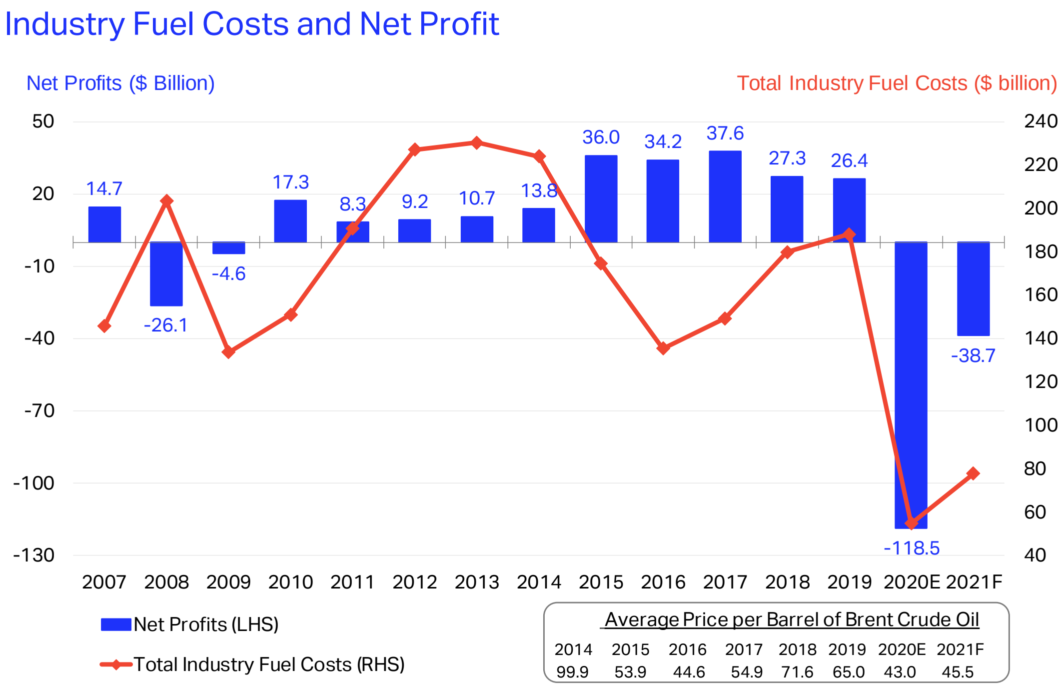
The EU-ETS is a way for the European Union (EU) to reduce greenhouse gas emissions [35]. It is the world's first major carbon market (since 2005) and remains the largest one. It covers around 45% of EU's greenhouse gas emissions. Companies receive or buy emission allowances, or it is possible to buy limited amounts of international credits from emission-saving projects. If a company doesn't have enough allowances at the end of the year, large fines are given. For aviation (since 2012), it only applies to flights between airports located in the European Economic Area (EEA).

Sustainable Aviation Fuels

The last lever is using sustainable aviation fuels to lower the life cycle emissions of the used fuel. Because the carbon mitigation measures above are not sufficient to reach goals, as has been shown in Figure 3.8, SAF is needed to accomplish that. This subject will be discussed later.

3.3.3. Aviation fuel economics and operations

Aviation fuel prices fluctuate, just as the crude oil prices. IATA [48] indicates that airlines had a 188 billion USD fuel bill in 2019, accounting for 23.7% of the operating expenses of airlines. However, the COVID-19 crisis and the related decrease in crude oil prices led to an estimated total fuel bill of 54.7 billion USD in 2020, which accounts for 12.7% of the operating expenses. The trend of fuel costs since 2007 can be seen in Figure 3.10.



2014	2015	2016	2017	2018	2019	2020E	2021F
99.9	53.9	44.6	54.9	71.6	65.0	43.0	45.5

Source: IATA
Updated: 11/2020 Next Update: 06/2021

Figure 3.10: Airline industry fuel costs over the years. Adapted from IATA [48]

To minimise risks of price fluctuations, most airlines use fuel hedging to protect them from unforeseen fuel costs. KLM Royal Dutch Airlines [68] explains how fuel hedging works in practice. Their strategy is to have a hedge horizon of 2 years with their fuel supplier. The first three quarters of the contract, a minimum of 60% of the fuel volume must be hedged fuel. This percentage gradually declines as the contract is nearing its end, as can be seen in Table 3.3. The rest of the fuel is bought freely on the market, which means that price fluctuations will affect these amounts.

Table 3.3: KLM fuel hedge strategy

Quarter	Minimum hedge percentage
Q1	60%
Q2	60%
Q3	60%
Q4	50%
Q5	40%
Q6	30%
Q7	20%
Q8	10%

Hedging, in its current form, would probably not be useful for SAF. Multiple airlines are setting up agreements with suppliers to have a guaranteed supply of SAF in the coming years. Although contracts between airlines and suppliers are not publicly accessible, we can assume that there would be a 100% hedge percentage for SAF during the agreement's length. There is little supply on the market now, so airlines wouldn't be able to buy extra SAF without an offtake agreement.

Normally, the fuel of an aircraft is uplifted (fuelled) in liter (equivalent to 0.2642 USG) (l) or US gallons (equivalent to 3.7850 l) (USG). However, the calculation to CO_2 is calculated from kilogram (kg), with 1 kg of CAF being equal to 3.16 kg of CO_2. To calculate the uplift in kg, a standard value density of 0.8 kg/l is used [32].

3.4. SAF characteristics

SAF is a term that is normally referred to non-fossil derived aviation fuel [4]. Three key elements characterise it. It needs to be **Sustainable**, which is defined as something that can be repeatedly and continually resourced in a manner that is consistent with economic, social and environmental aims, which is also called the ”triple-bottom-line” framework [109] which can be seen in Table 3.4. It also needs to conserve an ecological balance by avoiding the depletion of natural resources. **Alternative** feedstock to crude oil must be used, which includes any materials or substances that can be used as fuels, other than conventional, fossil-sources (i.e. oil, coal, and natural gas). Feedstocks are varied; they can, for instance, be cooking oil, plant oil, municipal waste, waste gases, and agricultural residues. The outcome is **Jet Fuel** that must meet the technical and certification requirements for use in existing commercial aircraft, and can be blended with conventional (fossil) jet fuel.

Table 3.4: Triple Bottom Line framework for Sustainability according to Slaper and Hall [109]

Economic measures	Environmental measures	Social measures
Personal income	Sulfur dioxide concentration	Unemployment rate
Cost of underemployment	Concentration of nitrogen oxides	Female labor force participation rate
Establishment churn	Selected priority pollutants	Median household income
Establishment sizes	Excessive nutrients	Relative poverty
Job growth	Electricity consumption	Percentage of population with a post-secondary degree or certificate
Employment distribution by sector	Fossil fuel consumption	
Percentage of firms in each sector	Solid waste management	Average commute time
Revenue by sector contributing to gross state product	Hazardous waste management	Violent crimes per capita
	Change in land use/land cover	Health-adjusted life expectancy

Delta Air Lines [26] formulated a set of biofuel principles that is guiding their decision-making and investments in the area of SAF:

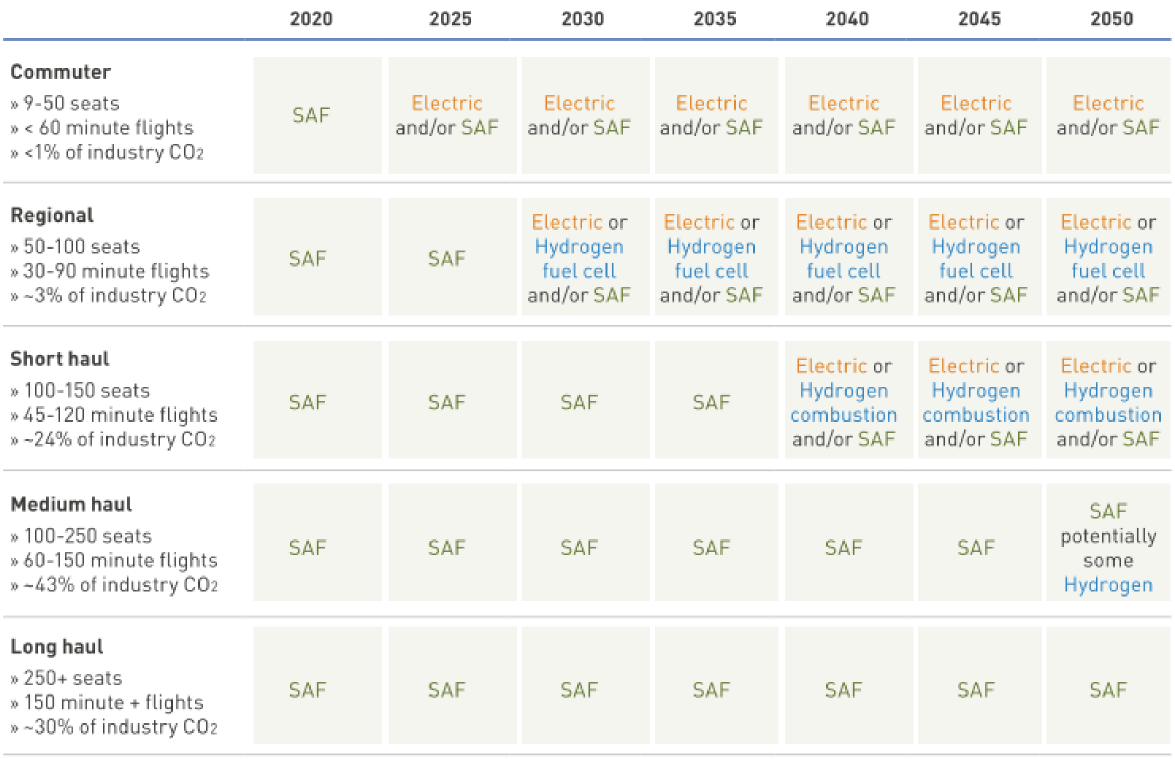
- It should meet technical and regulatory standards, including American Society for Testing and Materials (ASTM) D1655
- It should have a lower environmental impact (such as climate, water, air and biodiversity) than conventional petroleum-based fuel, including lower life-cycle carbon emissions.
- It should not come from feedstock that displaces or competes with food crops.
- It should satisfy technical and functional criteria that allow SAF to operate within the existing fuel transport, storage and logistics infrastructure.
- It should not have an adverse impact on aircraft engines.
- It should be reasonably cost-competitive with existing petroleum-based fuels.
- It should guarantee future availability.

Gegg et al. [38] state that the price of sustainable aviation fuel is at least two times as expensive as regular Jet A1 fuel. An assumption is that the price is the main barrier for airlines to adopt SAF. Besides that, a lack of feedstock, a lack of policy incentives and low funding limit the adoption of SAF.

3.4.1. SAF, Hydrogen or Electric propulsion

Although SAF would be a good solution, the industry is looking further than that. Aircraft configurations with electric propulsion are being developed and available after 2030 [137], but batteries are heavy and limit the range of aircraft. Besides that, hydrogen could be a valuable long-term alternative, because it's practically free of any life-cycle GHG. However, liquid hydrogen needs a large volume of well-insulated fuel tanks, making it inefficient for long distances [63]. Figure 3.11 from Air Transport Action Group [4] confirms this.

Considering that practically all TUI Aviation routes are more than 150 minutes (Southern Europe and Transatlantic) and that the time horizon for hydrogen on medium-haul is starting at 2050, the only feasible solution will be to use SAF.



	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-50 seats » < 60 minute flights » <1% of industry CO2	SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF	Electric and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO2	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO2	SAF	SAF	SAF	SAF	Electric or Hydrogen combustion and/or SAF	Electric or Hydrogen combustion and/or SAF	Electric or Hydrogen combustion and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO2	SAF	SAF	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen
Long haul » 250+ seats » 150 minute + flights » ~30% of industry CO2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Figure 3.11: Overview of technologies and ranges. Adapted from Air Transport Action Group [4]

3.4.2. Feedstocks

There are numerous feedstocks possible to develop SAF. Feedstock production is the first step in the production of SAF. There are different ways to categorise these feedstocks. In the text below, the feedstocks are categorised by the usable materials, which are sugar, oil, and lignocellulosic material.

Sugar or starch-bearing feedstocks are fermentable plants, which can be transformed into alcohol, from which SAF can be obtained [52]. In some processes, it is possible to make SAF directly out of sugars. Sugar-bearing plants can be sugarcane, sugar beet, and sorghum. Brazil, India and China are major producers. Starch-bearing plants could be maise, wheat, and cassava. The sugars are not directly available but must be obtained from the starches through chemical reactions. The United States is the primary producer of starches.

Oil-bearing feedstocks are a widely used feedstock and can be transformed into SAF by hydrogen addition [52]. The primary oil-bearing plants are palm and soybean, with the USA and Brazil as leading producers of soybean. In contrast, the production of palm oil is large in Malaysia and Indonesia. Two innovative plants are jatropha and camelina, which are non-edible and have potential high oil yields. Another new possibility is to extract SAF from Used Cooking Oil (UCO), and residual animal fats from the meat-processing industry, such as tallow and yellow grease. The main advantage is that no agricultural land is needed to get this feedstock.

Another main feedstock category is the use of lignocellulosic feedstocks, such as wood and wood residues, obtained from rotation forestry, or as residues from wood processing industries. The main advantage is that these alternatives do not conflict with food production. Agricultural residues could also be used, such as leaves, straw, bagasse, stalks and husks [52]. Municipal solid waste is also a lignocellulosic feedstock. The organic materials will be used after removing the recyclable materials such as glass, plastics and metals.

First and second generation

Not all examples described above are sustainable, such as palm oil. A feedstock can be either be a first or second-generation feedstock [101]. A first-generation feedstock can be used for producing both fuel and food, therefore conflicting world food supply. Besides that, there is less promise in reducing $\mathrm{CO_2}$ emissions. An example of a first-generation feedstock is palm-oil.

Many stakeholders (governments, non-governmental organisations, and other airlines) solely focus on second-generation fuels to avoid the issues stated above. ICAO [56] provided a list of possible feedstock materials that are classified as sustainable (Table 3.5).

3.4.3. Production pathways

There is a variety of pathways possible to produce SAF. These pathways differ in technological readiness, production costs, emissions reduction and maximum blend ratio. Aircraft will be fuelled in different countries and areas of the world, making it essential that all fuels have the same qualities and characteristics. And because SAF is a ”drop-in” fuel that is blended into CAF, sustainable fuel needs to have the same qualities and characteristics as conventional fuel, independent of the production pathway.

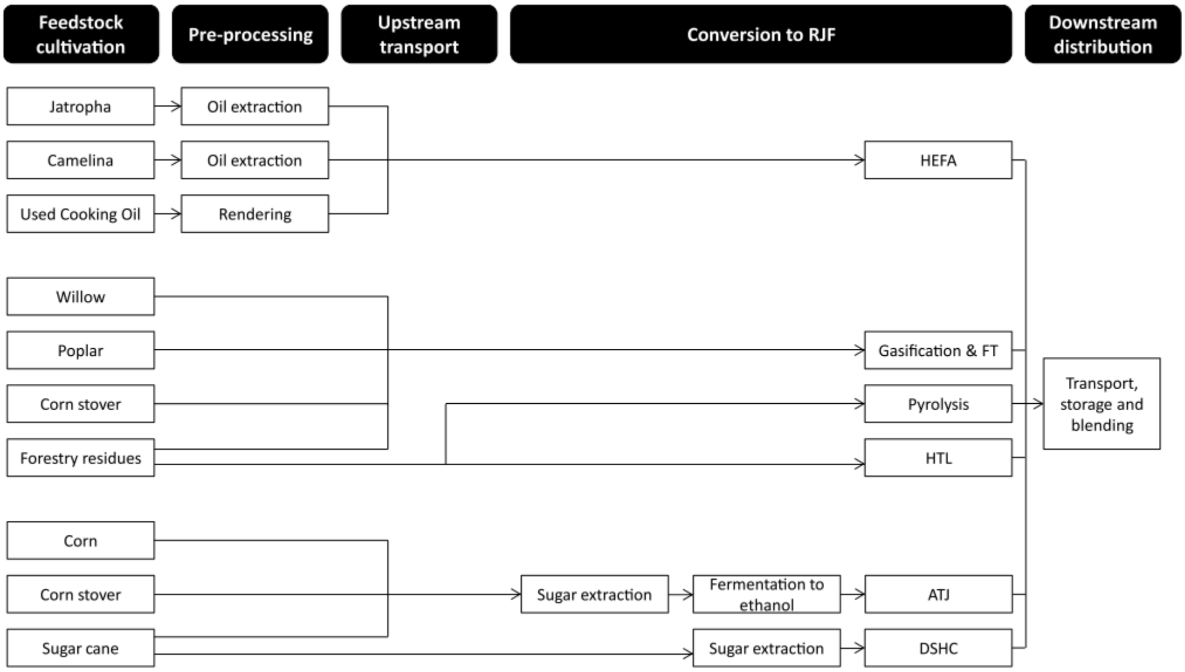


Figure 3.12: The scope of alternative fuel conversion pathways. Adapted from De Jong et al. [25]

Table 3.5: Positive list of materials classified as residues, wastes or by-products. Adapted from ICAO [56]

Residues	Argicultural residues	Bagasse Cobs Stover Husks Manure Nutshells Stalks Straw
	Forestry residues	Bark Branches Cutter shavings Leaves Needles Pre-commercial thinnings Slash Tree tops
	Processing residues	Crude glycerine Forestry processing residues Empty palm fruit bunches Palm oil mill effluent Sewage sludge Crude Tall Oil Tall oil pitch
Wastes		Municipal solid waste Used cooking oil
By-products		Palm Fatty Acid Distillate Tallow Technical corn oil

The most widely recognised standard to ensure conventional fuel is fit for purpose is the ASTM standard number D1655 [47]. ASTM sets requirements for criteria that are important for jet fuel, such as composition, volatility, fluidity, combustion, corrosion, thermal stability, contaminants, and additives.

The standard that handles the certification of SAF is ASTM D7566 [47]. If this certification accepts a technology, it is evaluated that this technology can produce SAF under specific circumstances and characteristics, as can be seen in Table 3.6. The certification of the fuel does not necessarily mean that the fuel is sustainable. Numerous feedstock options qualify with ASTM, but fail to reduce emissions, such as coal use.

There are three main production processes in production at the moment [47]. The first is Hydroprocessed Esters and Fatty Acids (HEFA), which can use oil-bearing feedstock such as UCO or Non-Food Plant Oil (NFPO) (such as Carinata seeds) to produce the fuel. The second is Fischer-Tropsch (FT), which uses either Municipal Solid Waste (MSW), Agricultural Residues (AR), or Forestry Residues (FR) as a feedstock. The latter is Alcohol-to-Jet (ATJ), which often uses sugar-bearing feedstock, but it is also possible to use other resources like MSW. A new and extra process is Hydroprocessed Fermented Sugars (HFS) (or DSHC),

Table 3.6: Approved conversion processes by ASTM.

ASTM	Conversion process	Abbreviation	Feedstock options	Blending ratio
D7566 Annex 1	Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene	FT-SPK	Coal, natural gas, biomass (forestry residues, grasses, municipal solid waste)	50%
D7566 Annex 2	Synthesised paraffinic kerosene from hydroprocessed esters and fatty acids	HEFA-SPK	Bio-oils, animal fat, recycled oils (algae, jatropha, camelina, used cooking oil, palm)	50%
D7566 Annex 3	Synthesised iso-paraffins from hydroprocessed fermented sugars	HFS-SIP	Sugarcane, sugar beet	10%
D7566 Annex 4	Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	Coal, natural gas, biomass (municipal solid waste, agricultural wastes and forestry residues, wood and energy crops)	50%
D7566 Annex 5	Alcohol to jet synthetic paraffinic kerosene	ATJ-SPK	Biomass from ethanol or isobutanol production (stover, grasses, forestry slash, crop straws, Sugarcane, sugar beet, sawdust)	50%
D7566 Annex 6	Catalytic hydrothermolysis jet fuel	CHJ	Waste or energy oils, triglycerides (soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil)	50%
D7566 Annex 7	Synthesised paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids	HC-HEFA-SPK	Oils produced from (botryococcus braunii) algae	10%
D1655	Co-processing		Fats, oils, and greases (FOG) from petroleum refining	5%

which resembles with ATJ because they both use sugar-bearing feedstock. The addition of Synthesized Paraffinic Kerosene (SPK) and Synthetic Iso-paraffin (SIP) in the abbreviations of the fuels indicate the resulting chemical products of the conversion processes.

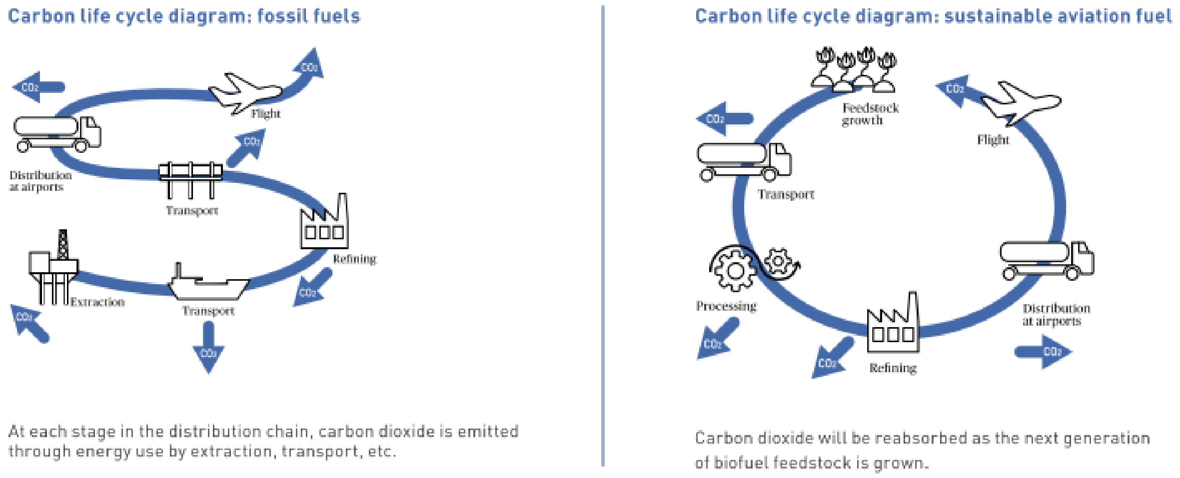
Power-to-Liquid

One other innovation regarding fuel conversion pathways is the production of Power-to-Liquid (PtL) fuels. This innovation uses carbon and energy to produce a more sustainable fuel [13]. The fuel could have a 100% reduction in carbon emissions if the electricity is coming from sustainable sources. Drünert et al. [31] note that a German market ramp-up in 2030 could solely be supplied by carbon from industrial point sources, but by 2050 a large-scale introduction of Direct Air Capture would be needed to supply the German aviation market. To convert that captured CO_2 in 2050, energy quantities are needed that equal the current total energy production in Germany.

The main disadvantage of Power-to-Liquid fuels is that there is no ASTM approval yet [31]. Currently, there are no production facilities that have planned to produce large quantities of PtL fuels. Besides that, the costs are estimated to be much higher than the use of HEFA fuels, becoming cost competitive with fossil fuel after 2030 [13]. Therefore, the introduction of this fuel is primarily a possibility in the medium- to long-term.

3.4.4. Life Cycle Assessment

Although it is a common thought that biofuels are climate neutral, this is not true. The production, conversion, and transportation of these novel fuels cause emission of GHG. Therefore, Life Cycle Assessment (LCA) is a tool to determine the environmental impact of fuels. LCA addresses the environmental aspects and their potential impacts throughout the life cycle of a product [52]. With a comprehensive scope, the aim is to avoid shifting problems, from one phase of the life cycle to another, or from one region to another.


Carbon life cycle diagram: fossil fuels

At each stage in the distribution chain, carbon dioxide is emitted through energy use by extraction, transport, etc.

Carbon life cycle diagram: sustainable aviation fuel

Carbon dioxide will be reabsorbed as the next generation of biofuel feedstock is grown.

Figure 3.13: Carbon life cycle diagrams for CAF and SAF. Adapted from Air Transport Action Group [4]

In aviation, this is known as Well-to-Wake analysis; with the two phases Well-to-Tank (WTT) and Tank-to-Wake (TTW) [94]. Although the combustion (TTW) emissions are the same for traditional Jet A1 fuel and SAF, the latter fuel can reduce life cycle CO_2 emissions by up to 80% [69]. These savings are achieved in the feedstock production and conversion process into biofuels (WTT) compared to fossil fuels.

Land Use Change

Greenhouse gas emissions that are associated with Land Use Change (LUC) are one of the main issues regarding LCA [52]. The production of biofuel feedstock, directly and indirectly, leads to changes in agricultural land use, this is called dLUC and iLUC. The direct effect is that land is needed to produce the feedstock, which is either taken from agricultural land previously used for food production, or natural vegetation such as forests. iLUC is the effect of food production needing to move to another place (mostly out of scope), for which new agricultural land is required. This is visually explained in Figure 3.14.

The conversion of natural vegetation to agricultural land results in a decrease in carbon in above and below-ground biomass. These iLUC emissions can be significant and reduce the efficiency of using biofuels to mitigate conventional fuel emissions. iLUC can not be directly measured; thus, economic models are needed to capture both effects together.

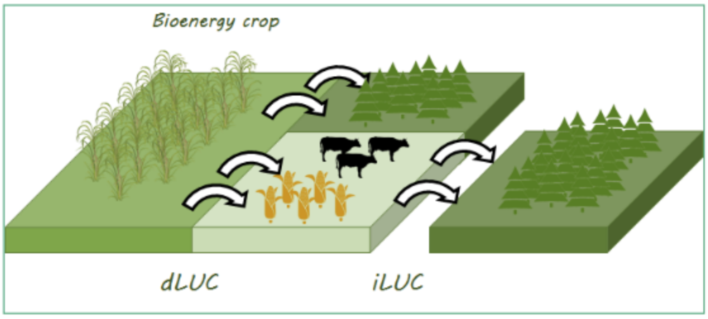


Figure 3.14: Schematic representation of direct and indirect land use change. Adapted from ICAO [52]

3.4.5. Minimum Selling Price

The Minimum selling price (MSP) for fuel is the price that producers of a fuel can afford to ask customers to fulfil the production's capital and operational expenditures. Some researchers, like Capaz et al. [19], stated their MSP in another unit of measurement, such as USD/GJ. With the use of Lower Heating Values, these values could be converted to USD/t. Pavlenko et al. [95] used the unit $€/liter$, which has been converted with the density values of the fuels and an exchange rate of 1 EUR = 1.13 USD in March 2019. Li et al. [73] had been added as an additional source because many other researchers did not take rapeseed oil into account.

The following criteria have been used to assemble a preliminary list of fuels that are included in this research:

- The fuel conversion process needs to be technically accepted by ASTM to be blended into fossil jet fuel. That means that future technologies (such as Power-to-Liquid) are not part of this research.
- The feedstock of the fuel needs to be eligible to CORSIA requirements (see subsection 3.1.1 and ICAO [54]), otherwise the fuel will be classified as conventional jet fuel, with the implication that the airline operator is still subject to offsetting requirements (and thus payments).
- Although the fuel that will ultimately be implemented may not be a first-generation fuel (that conflicts with food production), there has been chosen to include these in the research to show the differences in carbon mitigation and associated costs.

The 26-month Moving Average price of fossil jet fuel (Jet-A1) is 362 USD per tonne [59]. Therefore, the expected prices in Table 3.7 are 3 to 17 times higher than the use of fossil fuel (the most expensive being HFS-SIP). However, with increased production, SAF prices could decrease in the future. With the use of the experience curve theory in section 3.5, the future SAF prices could be determined.

Table 3.7: The minimum selling price of SAF according to various sources (USD/t)

Sustainable Aviation Fuel	Bann et al. [11]	Capaz et al. [19]	de Jong et al. [24]	ICAO [52]	ICAO [51]	Li et al. [73]	Pavlenko et al. [95]	Staples et al. [114]	Vela-García et al. [127]	Wei et al. [133]	Wang et al. [130]
ATJ-SPK Agricultural residues	3342.21	1810.46	3384.80	2330.23	2500.00		3611.19		1514.20	2678.66	1512.57
ATJ-SPK Corn grain	2210.39	1484.49		2077.23	2150.00		2512.78	2321.62		1841.47	
ATJ-SPK Forestry residues	3342.21	1810.46	2488.83	2396.80	2500.00		3611.19			2678.66	3482.43
ATJ-SPK Miscanthus	3342.21	1810.46		2396.80	3250.00		3686.42			2678.66	
ATJ-SPK Sugarcane	1957.39	1484.49		2077.23	1900.00		2482.69	2075.39		2063.07	
ATJ-SPK Switchgrass	3342.21	1810.46		3062.58	3250.00		3686.42	3060.32		2678.66	
FT-SPK Agricultural residues	2000.00	1428.84	2591.32	1184.21	1050.00		2676.32			2398.40	
FT-SPK Forestry residues	2000.00	1428.84	1843.82	1552.63	1500.00		2676.32			2398.40	
FT-SPK Miscanthus	2000.00	1428.84		2578.95			2780.39			2398.40	
FT-SPK Municipal solid waste	1513.16				1550.00		1992.37				
FT-SPK Poplar	2000.00	1428.84		1552.63	1500.00		2780.39			2398.40	2155.09
FT-SPK Switchgrass	2000.00	1428.84		1447.37	1500.00		2780.39			2398.40	
HEFA-SPK Corn oil				1375.17	1450.00					1250.32	
HEFA-SPK Palm fatty acid distillate				1375.17	1450.00		1478.50			1250.32	
HEFA-SPK Palm oil - closed pond		1528.35		1001.34	750.00		1508.68				
HEFA-SPK Palm oil - open pond		1528.35		1001.34	750.00		1508.68				
HEFA-SPK Rapeseed oil				1068.09	1150.00	1415.22				1102.19	917.02
HEFA-SPK Soybean oil	1588.79	1612.52		1448.60	1450.00		1644.46			1447.83	1551.88
HEFA-SPK Tallow	1415.22	1528.35		1535.38	1480.00					1250.32	
HEFA-SPK Used Cooking Oil	1214.95	1258.12	1501.77	1295.06	1300.00		1327.64			1250.32	
HFS-SIP Sugar beet			6045.50				5451.75			2373.58	2582.13
HFS-SIP Sugarcane			6045.50				5451.75			2373.58	2582.13

3.5. Experience curve theory

Festel et al. [37] use a scaling and learning effects methodology to analyse biofuels conversion technologies. The scaling effects refer to the production scale size, while technological advantages cause the learning effects. Scaling effects would be static as they do not change automatically over time unless the production capacities are expanded. These effects mainly consist of marginal costs per unit that are below average costs, which makes it cheaper to produce more units. However, learning effects would be dynamic in nature (with a diminishing impact over time). The learning effects are scale-independent and lead to a more efficient organisation of production and transportation processes, the use of advanced materials, and lifetime prolongation of catalysts.

Weiss et al. [134] describes the origin of the experience curve approach. Wright [135] showed that unit labour costs declined at a constant rate with each doubling of cumulative production in airframe manufacturing in the 1930s. His graphical representation is nowadays referred to as the learning curve. This can apply to the effects of learning-by-doing, thus reducing labour costs due to a reduction of working time requirements for airframe manufacturing. Later research showed that declining labour costs are a result of growing experience [134]. A differentiation between experiences curves and progress curves is made; the first curve represents the average production costs of multiple manufacturers (cumulative production). The second represents production costs at the level of individual businesses.

The experience curve formulated by Weiss et al. [134] expresses production costs (or prices) of technologies as a power-law function of cumulative production.

$$Ccum_i = C_{0,i} * (Pcum_i)^{b_i} \tag{3.3}$$

In this equation, $Ccum_i$ represents the price or costs at the cumulative production $Pcum_i$. The price or costs of the first unit produced is defined as $C_{o.i}$, while b_i is the technology-specific experience index of technology i (in this case, SAF alternative i). The resulting logarithmic function of Equation 3.3 gives a linear experience curve that can be plotted with b_i as the slope parameter and log $C_{o,i}$ as the price or cost axis intercept.

A technology-specific process ratio (PR_i) and a learning rate (LR_i) can be calculated with the formulas below. The learning rate can be defined as the rate at which a technology's price or costs decreases with each doubling of cumulative production [134].

$$PR_i = 2^{b_i} \tag{3.4}$$

$$LR_i = 1 - PR_i = 1 - 2^{b_i} \tag{3.5}$$

A PR_i of 0.7 (or 70%) means that with every doubling of cumulative production, the production costs decline with 30%, which is defined as the learning rate LR_i. In most studies and industries, it is common to have a PR_i in between 0.7 and 0.9. The method has been used for various products, such as computer chips, aircraft, light bulbs and chemical compounds [125].

According to Chao et al. [22], a PR_i of 0.81 can be used for the bio-ethanol industry. Therefore, doubling the cumulative bio-ethanol production would lead to a 19% decrease in production costs (or price). The bio-ethanol industry does not have the same processes as the production of sustainable aviation fuel; thus it is wise to start with a PR_i of 0.9 to prevent overestimating price decrease, while a sensitivity analysis can find out the effect of the PR_i equal to 0.81 and/or other values.

However, Mawhood et al. [81] note that HEFA technology is mature and already deployed at a commercial scale. Growth in HEFA technology is limited due to the limited availability of sustainable feedstock. Therefore, Cervi et al. [21] conclude that learning effects are not considered with HEFA technologies. In contrast, biomass yield development and learning effects of biomass pretreatment and ATJ technology will be primary drivers for increasing scales toward 2030. Leila et al. [72] confirm that technology learning has minimal effect on the HEFA production.

3.6. Conclusion

This chapter has been a preparation for the analysis in the following chapters. The traffic forecasts, sector characteristics, SAF characteristics, experience curve theory, and stakeholders and regulations will all be used in the analytical model. This theoretical chapter already answers some sub-questions of this thesis. Other sub-questions are not answered yet, but background information is given in this chapter in order to answer these sub-questions with the analytical model in the following chapters.

> 1. What stakeholders in commercial aviation are involved and what are the regulations, policies and goals regarding SAF that they have set?

As has been described in section 3.1, some international organisations have set guidelines and/or regulations to ensure a more sustainable aviation sector. The United Nations set 17 goals to achieve a better and more sustainable future, of which two are related to carbon mitigation. The International Civil Aviation Organization (ICAO) is going further by setting up binding policies for all member states and their airlines. This involves implementing the CORSIA carbon mitigation scheme, ensuring carbon-neutral growth for all member state airlines from 2021.

ICAO also required that CORSIA eligible fuels should have emissions reductions of at least 10% compared to fossil fuel. The European Union is going even further and requires SAF to have at least 50% to 65%, depending on the age of the production installation.

National governments are pushing the aviation industry towards more sustainable levels by introducing SAF quota. Scandinavian countries are acting at the forefront, striving for a SAF blending mandate of 30% in 2030. The Netherlands follows with a 14% mandate.

The airline industry generally embraces two goals. The International Air Transport Association (IATA) promised to emit 50% fewer carbon emissions in 2050 compared to the industry's 2005 emissions. However, some airlines further than that and commit to a carbon-neutral operation by 2050.

> 5. What SAF innovations are currently in development or on the market?

There are multiple feedstock possibilities and production pathways available to produce SAF. One of the most popular production pathways at the moment is the use of HEFA, mostly in combination with used cooking oil or any other oil-bearing source. Most important for a renewable fuel is the certification, as it is only allowed to use a fuel after it's certified to be blended into fossil jet fuel. Therefore, only fuels that comply with certification ASTM D7566 are included in this research.

4

Conceptual Model

This chapter will start with a description of the purpose of the conceptual model in section 4.1. Then, the assumptions will be discussed in section 4.2, followed by a description of the input and output in section 4.3. The chapter will finish with a description of the calculations in the model in section 4.4.

The purpose of a conceptual model is to give a representation of the fundamental principles and the basic functionality of the computerised model that is being developed. According to Kung and Sölvberg [70], a conceptual model needs to enhance the understanding of the representative system for an individual, it needs to facilitate an efficient conveyance of system details between stakeholders, it is a point of reference to extract system specifications for system designers, and it provides a means for collaboration by documenting the system for future reference.

4.1. Purpose of this model

The development of the model is inspired by the CO_2 emissions forecasting method from ATAG [4]. This method has been described earlier in section 2.3 and can be found in Figure 4.1. The ATAG method is developed to measure the effects of (1) traffic forecasts, (2) fleet fuel burn forecasts, (3) effects of technology and operations, (4) effects of alternative fuels, and (5) the effects of emission reductions from other sectors (Market-Based Measures).

The CO_2 forecasting process should meet the carbon goal after all steps described above are included. If not, some steps of the CO_2 forecasting process need additional interventions by adjusting assumptions, such as SAF offtake quantities. This process is called backcasting. In this approach, the modelling assumptions are adjusted, such that the resulting carbon emissions forecast meets the carbon goal [4].

Backcasting is possible by changing one or multiple steps above to see the effects on the CO_2 forecast and continue until the carbon goal has been met. To give an example; by changing the effects of alternative fuels (i.e. by implementing higher quantities), it could be ensured that the carbon goal could be met (i.e. by more carbon mitigation resulting from higher quantities).

The conceptual model (Figure 4.2) developed for this research is based on the ATAG-model [4], but some extra dimensions are added. The backcasting principle is an integral part of this model; the goal (or carbon reduction scenarios in this case) is determined after the effects of technology and operations (step 3). The ”carbon reduction gap” then needs to be filled by introducing the effects of SAF and Market-Based Measures. Therefore, step 4 and 5 are done in a later phase.

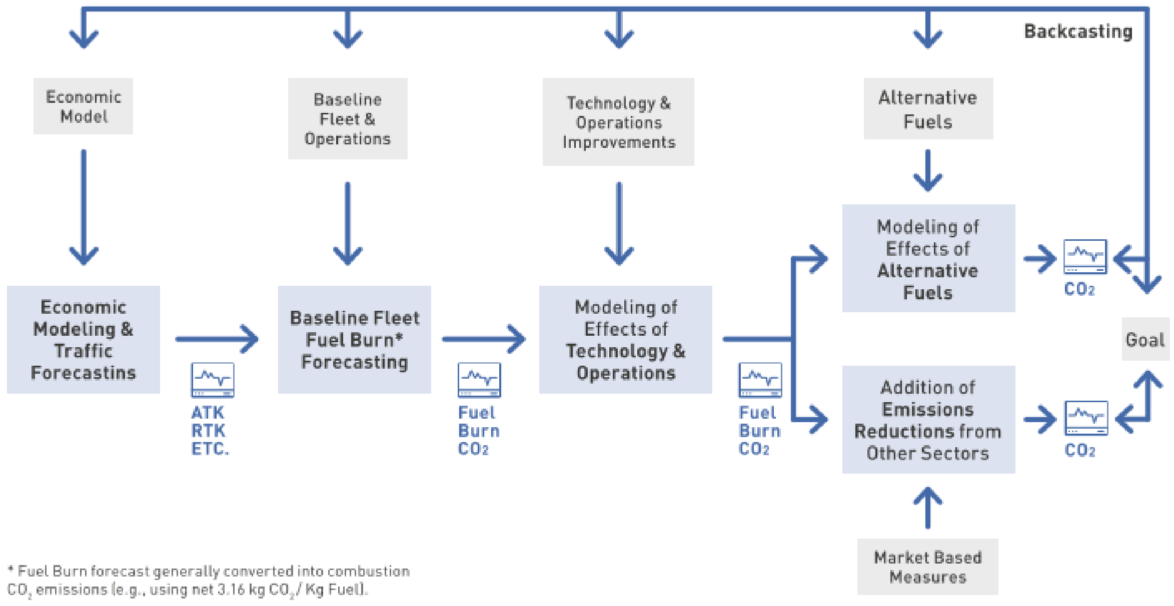


Figure 4.1: Method for forecasting CO_2 emissions. Adapted from Air Transport Action Group [4]

Initially, the ATAG-method [4] included the effects of SAF and the effects of MBM after the effects of Technology and Operations, which resulted in the goal on the right-hand side of Figure 4.1. In the conceptual model in Figure 4.2, these original process flows are visualised with intermittent grey arrows.

The conceptual model assumes that the carbon goal is determined first, and the the effects of SAF and MBM are included after. Hence, the backcasting principle is actively used. This results in new order of model components. This is shown with the double black arrows in Figure 4.2.

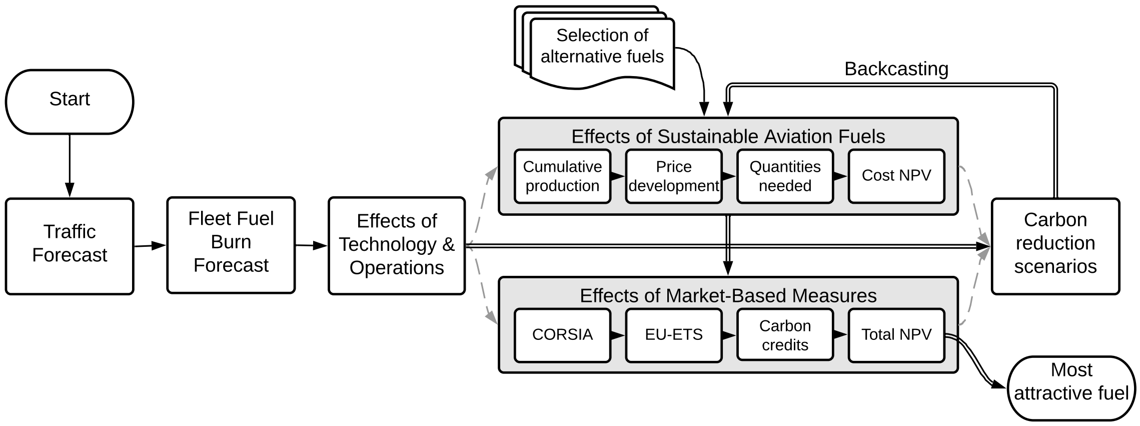


Figure 4.2: Conceptual Model. Grey intermittent arrows are not active anymore, replaced by double black arrows.

Zooming into these two processes, there can be seen that a lot of sub-processes are now part of the model. To start with the SAF effects, there is an initial selection of fuel alternatives (in Table 3.7) that are added to the model. These alternatives are all analysed in four sub-processes. At first, the cumulative production of fuel alternatives is determined, after which the price development of those fuels is calculated by using the experience curve method. These fuel alternatives have different carbon reduction power, so quantities needed to reach specific goals will differ per fuel alternative. After calculating these quantities, the costs could be determined by combining the quantities with the calculated prices, and then converted to a Net Present Value.

For the Market-Based Measures process, there are also four sub-processes. At first, the cost reduction of the compulsory CORSIA and EU-ETS schemes is determined for all fuels. In a no-action scenario without SAF, there would be more costs related to these schemes. Thus the reduction of costs needs to be subtracted from the Net Present Value (NPV). Secondly, some fuel alternatives don't have the power to reach the carbon reduction required to meet goals. Therefore, the remaining ”carbon reduction gap” needs to be filled by introducing extra carbon offsetting in other sectors. These costs will be added to the NPV, which will result in the ultimate NPV for all fuel alternatives. The fuel with the lowest NPV would have the lowest implementation costs and is the most attractive fuel.

4.2. Assumptions

At first, there is the assumption that the conceptual model's traffic forecast takes the COVID-19 crisis into account. The severity of this crisis will have a considerable influence on traffic numbers in the coming years. Air Transport Action Group [4] did include the COVID-19 crisis in their methodology and results. Still, the ATAG-model only considers global recovery data and global growth data. It is expected that the market for TUI Aviation (tourism) will recover faster than the commercial aviation sector in general, as discussed in subsection 3.2.4.

Secondly, the conceptual model assumes that all SAF alternatives are technically ready and certified to use. This means that other fuels (i.e. Power-to-Liquid, discussed in subsection 3.4.3) are not part of the selection of alternative fuels that would be implemented in the model. If any new fuels/technologies would be certified in the future, the computerised model user should be able to add these fuels relatively easy.

Besides that, it is assumed that the introduction of SAF is the primary process to limit CO_2 emissions compared to the addition of emissions reductions from other sectors. This is contrary to the ATAG method, which assumes that SAF and reductions from other sectors can be used in any preferable order. As has been discussed in subsection 3.1.3, emissions reductions from other sectors (by voluntary carbon offsets) do not mitigate CO_2 immediately. Therefore the introduction of SAF is preferred.

It is assumed that the introduction of SAF would not decrease effects of contrails on radiative forcing (discussed in subsection 3.3.1). Therefore, the environmental effects of contrails are not part of this conceptual model.

4.3. Input and output of the model

The first input is the traffic data that will be used in the first step. These will be RPK and CO_2/RPK data from 2019 for step 1 and 2, extracted from the TUI flight database. Secondly, percentages will be used that indicate the technological and operational efficiency improvements in step 3. A major input component is the addition of SAF alternatives to the model in step 4, including carbon mitigation power, cumulative production, and pricing. In step 5, the effects of carbon reductions from other sectors will be added (thus costs per ton of mitigated carbon emissions). The goal would be input, too, resulting from the stakeholder and policy analysis. Although this is mentioned as output in the ATAG model, it is preferred to have this input in the conceptual model.

The main output will be the Net Present Value of the implementation of SAF alternatives. Because this output differs from the ATAG method, it is required to change the steps' order.

Therefore, the ”goal” will be defined after step 3, and after the determination of the goal, the analysis will continue with steps 4 and 5.

4.4. Calculations in the model

The components in the conceptual model mainly consist of calculations. The output of a model component is generally the result of calculations that have been done within that model component. The output of model components generally is input for the next model component.

4.4.1. Traffic forecast

At first, the RPK values (a standard KPI for demand) are determined. The RPK per flight can be calculated by multiplying the distance with the number of revenue passengers:

$$RPK_j = d_j * RP_j \tag{4.1}$$

Where RPK_j is the RPK for flight j, d_j is the distance of flight j in kilometres, and RP_j is the number of Revenue Passengers in flight j. The RPK of all flights is then summed, either for all flights or per attribute (such as per market i below):

$$F_{i,0} = \sum_{j=0}^{\infty} RPK_j \qquad \forall j \in i \tag{4.2}$$

Where $F_{i,0}$ is the RPK forecast for market i in year $t = 0$. Then, Compound Annual Growth Rates are used to determine the demand in future years. The CAGR is implemented in the following formula:

$$F_{i,t} = F_{i,t-1} * (1 + CAGR_i) \tag{4.3}$$

Where $F_{i,t}$ is the RPK forecast for market i in year t, and $CAGR_i$ is the Compound Annual Growth Rate per market i. The demand forecast $F_{i,t}$ is the output of this model component.

4.4.2. Fleet fuel burn forecast

The demand forecast output of the previous component will be transformed into a CO_2 forecast in this component. Therefore, a carbon efficiency KPI can be used: CE_i, which is the carbon efficiency in CO_2/RPK per market i. This variable is implemented in the following variables:

$$E_{i,t} = F_{i,t} * CE_i \tag{4.4}$$

$$E_t = \sum_{i=0}^{\infty} E_{i,t} \qquad \forall t \in [2020, 2050] \tag{4.5}$$

Where $E_{i,t}$ is the CO_2 emissions of market i in year t, $F_{i,t}$ is the demand forecast of market i in year t, and CE_i is the carbon efficiency of market i (in CO_2/RPK). A summation of $E_{i,t}$ in Equation 4.5 gives the total carbon emissions E_t per year as output in this model component.

4.4.3. Effects of Technology & Operations

Efficiency improvements from technology and operations will limit future CO_2 emissions in commercial aviation. These efficiency improvements will be deducted from the output E_t in the previous component by executing the formulas below:

$$OE = (1 + TOE)^{\frac{1}{30}} - 1 \tag{4.6}$$

$$EL_t = E_t * (1 - TE - OE)^{t-2019} \tag{4.7}$$

Where TOE is the Total Operational Efficiency improvement (in 30 years), OE is the Operational Efficiency improvement per year, TE is the Technological Efficiency improvement per year, and EL_t is the Emission Level in year t (after technological and operational efficiency improvements). The output of this model component is the EL_t.

4.4.4. Carbon reduction scenarios

Input for this model component is the EL_t calculated above. Besides that, a carbon mitigation start level and start year need to be determined by the user, that will be used as input (e.g., start with 1 % carbon mitigation in start year 2023).

In this model component, an annual growth factor of the chosen start level and year is calculated with the following formulas:

$$EG_{s,t} = EL_t * (1 - RP_{s,t}) \tag{4.8}$$

Where $EG_{s,t}$ is the Emission Goal for scenario s in year t, EL_t is the Emission Level in year t (after technological and operational efficiency improvements), and $RP_{s,t}$ is the Reduction Percentage for scenario s in year t. This can be rewritten in the following formula:

$$RP_{s,t} = 1 - \frac{EG_{s,t}}{EL_t} \tag{4.9}$$

With the availability of the Reduction Factor in 2050 and the start year and quantity of the mitigation project, the annual growth factor can be calculated:

$$GF_s = \overline{\frac{RP_{s,2050}}{RP_{s,SY_s}}}^{\frac{1}{2050-SY_s}} - 1 \tag{4.10}$$

Where GF_s is the Growth Factor of scenario s, $RP_{s,2050}$ is the Reduction Factor in 2050, RP_{s,SY_s} is the Reduction Percentage in starting year SY_s.

This Growth factor can calculate the annual carbon mitigation for all years until 2050. But to ensure that the resulting reduction factors comply with the governmental quota discussed in section 3.1, for every s and t the maximum is taken of $RP_{s,t}$ and the governmental mandates or quota, to ensure that governmental quota are being met:

$$Q_t = \sum_{k=1}^{\infty} Q_{k,t} * FS_k \qquad \forall t \in [2020, 2050] \tag{4.11}$$

Where Q_t is the total quota in year t, $Q_{k,t}$ is the quota of country k in year t, and FS_k is the Fuel Share of departures in country k out of the total fuel consumption of the company. This gives the final formula for the Effective RP and Effective EG that take the governmental quota into account:

$$ERP_{s,t} = \max(RP_{s,t}; Q_t) \tag{4.12}$$

$$EEG_{s,t} = EL_t * (1 - ERP_{s,t}) \tag{4.13}$$

4.4.5. Effects of Sustainable Aviation Fuels

This model component consists of four sub-processes, which are explained below.

Selection of alternative fuels

First, the emission reduction power of fuels is calculated. The Emission Reduction factor ER can be calculated to determine the quantity of CO_2 that is reduced by using a specific fuel. The following formula is used by ICAO [57]:

$$ER_t = FCF * \left[\sum_{f=1}^{\infty} MS_{i,t} * \left(1 - \frac{LS_f}{LC} \right) \right] \qquad \forall t \in [2020, 2050] \tag{4.14}$$

Where ER_t is the emissions reduction factor in year t, FCF is the fuel conversion factor (fixed value, 3.16 for Jet A1 fuel [kg CO_2 / kg fuel]), $MS_{i,t}$ is the total mass of a CORSIA eligible fuel claimed in the year t by fuel type i (in tonnes), LSf is the life cycle emissions factor of the SAF alternative, and LC is the baseline life cycle emissions (fixed value, 89 for Jet A1 fuel [gCO2e/MJ]).

The formula is meant to calculate the total reduction for a given fuel offtake within an airline operator. But with $MS_{i,t} = 1$, the emissions reduction per tonne fuel can be determined.

To calculate the total carbon reduction potential of alternative fuels, the following formula is used:

$$CRP_i = \frac{\frac{FAP_i}{FPS_i}}{LSf_i} \tag{4.15}$$

Where CRP_i is the carbon reduction potential of alternative i, FAP_i is the feedstock availability potential of alternative i, FPS_i is the feedstock needed per Mt SAF for alternative i, and LSf_i is the life cycle emissions factor.

Cumulative production

The next step is to calculate the cumulative production per SAF alternative. This will be done using the following formula:

$$CP_{i,t} = \sum_{i=0}^{\infty} P_{i,t} \qquad \forall t \in [2020, 2030] \tag{4.16}$$

Where $CP_{i,t}$ is the cumulative production of SAF alternative i in year t, and $P_{i,t}$ is the production of an individual producer. The output of this model component is $CP_{i,t}$.

Price development

Learning and scaling effects according to the experience theory can assure lower prices with increased production. The following formula is used, based on the theory in section 3.5 and the output $CP_{i,t}$ of the previous model component:

$$C_{i,t} = C_{i,t-1} * PR_i^{\log_2 \frac{CP_{i,t}}{CP_{i,t-1}}} \tag{4.17}$$

Where $C_{i,t}$ is the cost of SAF alternative i in year t, PR_i is the technology-specific process ratio, and $CP_{i,t}$ is the cumulative production of SAF alternative i in year t. The MSP in year $t = 2020$ is $C_{i,2020}$. This model component will lead to the expected cost $C_{i,t}$ as output.

Quantities needed

In this model component, output from ”carbon reduction scenarios” is used. With these data, the expected required fuel quantity can be determined.

$$FQ_{i,t,s} = \frac{EL_t - EG_{t,s}}{ER_i} \tag{4.18}$$

Where $FQ_{i,t,s}$ is the Fuel Quantity needed for fuel alternative i in year t and scenario s, EL_t is the Emissions Level (after the technological and operational improvements) in year t, $EG_{t,s}$ is the Emission Goal in year t and scenario s, and ER_i is the Emissions Reduction factor of fuel alternative i.

Cost NPV

In the previous two model components, the fuel price and fuel quantity have been specified. This output can be used as input in this component, where the total costs are calculated. The following formula is used:

$$TC_{i,t,s} = FQ_{i,t,s} * (C_{i,t} - C_{CAF}) \tag{4.19}$$

Where TCi,t,s is the total cost for alternative i, year t and scenario s, $FQ_{i,t,s}$ is the fuel quantity, $C_{i,t}$ is the cost of alternative i in year t, and C_{CAF} is the cost for conventional aviation fuel (fossil fuel).

The fuel costs per year are then summed over the years, taking into account a 10% discount rate to represent a Net Present Value. The following formula is used to calculate NPV:

$$NPV_{i,s} = \sum_{t=2020}^{2050} \frac{TC_{i,t,s}}{(1+i)^t} \tag{4.20}$$

Where $NPV_{i,s}$ is the Net Present Value for SAF alternative i in scenario s, TCi,t,s is the total cost for alternative i, year t and scenario s, and i is the discount rate or the return that could be earned in alternative investments (set at 10%).

5

Computerised Model

This chapter will focus on the execution of the computerised model. The equations discussed in section 4.4 are used in this model that is made in Microsoft Excel (*CO2 and SAF forecast thesis.xlsx*). The data collection is also discussed in this chapter.

In section 5.1, the analysis will start with the determination of air travel demand for the TUI Group in the period 2021-2050, taking into account the effects caused by COVID-19. In section 5.2, this projected demand will be converted to the estimated CO_2 emissions. In section 5.3, the carbon mitigation caused by external factors (technological and operational efficiency improvements) will be extracted from the carbon estimation. This new carbon projection will be used in section 5.4, where two carbon reduction scenarios are created based on the carbon estimation.

In section 5.5, the comparison of different SAF alternatives will occur. At first, the carbon mitigation values per SAF alternative will be calculated. This will determine the carbon reduction potential per fuel that defines the most preferred alternatives from a social perspective. After that, prices and production quantities will be determined that are used in an experience curve to measure future price trends. These values will be used in a business Cost-Benefit Analysis that determines SAF quantities and Net Present Value of costs to implement the SAF alternatives. In section 5.6, the addition of market-based measure (carbon pricing) benefits will be added to the model.

5.1. Traffic Forecast

The traffic forecast starts with the use of Equation 4.1 to determine the RPK values per flight. A data-set of 155,449 flights executed in 2019 has been used to perform this analysis. Equation 4.2 is used to determine the total RPK values per market i.

More than half of the RPK and CO_2 can be found within the British entity of the TUI Aviation Group; TUI Airways. The subsidiaries in Belgium, Germany and the Netherlands follow, with TUI fly Nordic (Sweden) closing the line. An overview can be found in Table 5.1.

As has been discussed in section 3.2, it is ambiguous to use global annual growth rates for aviation in a case study scenario, because that growth rate is influenced by upcoming Asian markets. ICAO [53] indicates expected growth curves per market. These growth rates can be found in Table 5.2 and are used in Equation 4.3.

In the model that is created (CO_2 and SAF forecast thesis.xlsx), the calculations and data above are used to create the traffic forecast. There is an extra functionality to consider the effects of COVID-19 in the traffic forecast. Via a Drop-Down list in tab A1 of the (Excel-based) model, the user can choose a recovery year. This recovery year gets the same RPK values

Table 5.1: The five airlines included in this analysis

Airline	Number of flights	Share in RPK	Share in CO_2
TUI Airways	65,011	51.7%	50.64%
TUI fly Belgium	37,819	15.5%	16.78%
TUI fly Deutschland	35,647	18.3%	18.22%
TUI fly Netherlands	13,415	11.7%	11.62%
TUI fly Nordic	3,557	2.8%	2.74%
Total	155,449	100%	100%

Table 5.2: Compound Annual Growth Rates. Adapted from ICAO [53].

Market	30 year CAGR
Intra Europe	2.6%
Europe <-> Central America / Caribbean	3.8%
Europe <-> Central and South-West Asia	5.1%
Europe <-> Middle East	4.0%
Europe <-> North Africa	4.1%
Europe <-> North America	2.6%
Europe <-> Pacific South-East Asia	4.4%
Europe <-> South America	4.1%
Europe <-> Sub Saharan Africa	2.8%

like 2019, and the following years will be calculated using the formula above. In section 3.2, a study has been performed into the aviation's expected recovery year. Assuming that tourism demand will recover sooner than aviation in general (that includes business traffic), the recovery year in the model is set at 2023 for now.

The years before the recovery year (e.g. 2020-2022) will get a standard value 0 for RPK demand. There are three main reasons to use this limitation. At first, demand during the COVID-19 recovery period is practically impossible to forecast due to external factors, such as possible new COVID-19 infection waves, closed borders, and other travel-restricting policies. Besides that, one can assume that airlines won't invest large amounts of money in crisis times. The third reason is the resulting CO_2 emissions in the recovery period will not equal the CORSIA baseline emissions of 2019, which means there is no financial incentive to invest in carbon reduction during the recovery period.

An additional distinction is made in the model by including the relevance to the EU-ETS and CORSIA carbon mitigation schemes per market, as can be seen in Table E1 (confidential appendix, not included in public version). Although this information is not needed to estimate demand, the data is useful for other steps that will be executed later in this analysis.

The result of this process is a demand forecast for the period 2020-2050 that is specified into different markets. A summation of these market demands gives the total demand forecast.

5.2. Fleet Fuel Burn Forecast

The next step is to estimate the fuel burn and the resulting emissions from the demand forecast with the use of Equation 4.4 and Equation 4.5.

TUI Aviation works with company-wide CO_2/RPK values to measure carbon efficiency, but it is more accurate to calculate the CO_2/RPK per market i. For instance, longer flights mostly have a lower CO_2/RPK, because the relatively high amount of fuel burned during take-off has a lower share in the total flight compared to short flights. Besides that, different aircraft types are used within the company, with some types only being able to perform shorter flights due to their range.

The TUI data can be found in Table E1 (confidential appendix, not included in public version). There are three outliers in CO_2/RPK with more than 0.1 kg CO_2 per RPK (others are around 0.07 kg). These outliers contain a lot of technical and positioning flights, which are without paying passengers. The absence of passengers influences the RPK of those flights (low RP_j in Equation 4.1). There has been chosen to include these outliers in the model, because these technical and positioning flights will be operated in the future, too.

The result of this process is a summation of all CO_2 emissions per year.

5.3. Effects of Technology & Operations

In Figure 3.3.2 and Figure 3.3.2, the technological and operational efficiency improvements have been discussed. Decided was to use a 1% per year technological efficiency improvement, which refers to introducing more efficient aircraft that replace less fuel-efficient ones. Operational improvement is estimated at 6% in total until 2050, which can be achieved by, i.e. better Air Traffic Management.

Equation 4.6 and Equation 4.7 are implemented in Excel to determine the CO_2 after technological and operational efficiency improvements. In tab A3 of the model, these two variables can be changed to the user's wish.

5.4. Carbon reduction scenarios

Before the effects of alternative fuels can be measured, it is needed to know how many carbon emissions need to be mitigated. As has been discussed in section 3.1, there are multiple obligations in the sector, of which the most important one is to halve the carbon emissions in 2050 compared to 2005. Besides that, some governments mandate to use a minimum percentage of fuel for years ahead; thus, it is important what the minimum carbon reduction per year must be.

The first scenario is to limit the carbon emissions to 50% of the levels emitted in 2005. However, no reliable data of TUI's 2005 operations can be found, partially because, i.e. TUI fly Netherlands did not even exist at the start of 2005. Besides that, the objective set by IATA is to limit the emissions on a global level, not on an airline operator level.

Therefore, the share of TUI's aviation emissions within the global aviation emissions in 2019 is extrapolated to 2005. As shown in the model in tab A2, the total emissions of TUI in 2019 were 5.3 Mt, while the global aviation emissions were 914 Mt [3]. Considering that global aviation accounted for 733 Mt in 2005 [71], an extrapolation of TUI's share results in 4.2 Mt. A 50% reduction of this level gives a 2.1 Mt carbon emission goal for 2050.

The net-zero emission scenario is the second and most rigorous scenario. Some airlines already confirmed to strive toward this scenario, which can be found in section 3.1. Instead of emitting a maximum of 2.11 Mt of CO_2, it is the goal to keep the emission levels in 2050 at 0 Mt.

The model gives two parameters per scenario that can be changed by the user, as can be seen in tab A5 of the model. A starting year must be formulated for the company to start with the mitigation "road map", thus the implementation of SAF. The second is the start level of these carbon mitigation levels as a percentage of total CO_2 emissions. This can be done for each scenario separately. In the model, there is assumed that TUI will start in 2023, to align with the demand forecast recovery year and to ensure that not a lot of investments need to be made during times of crisis. The start level is set at 1.0% carbon mitigation (as a reduction percentage of total CO_2 emissions).

With the use of Equation 4.8 till Equation 4.13 the two carbon reduction scenarios can be calculated, which can be seen in tab A5 of the model. The result is that the two scenarios described above have stated the minimum carbon mitigation for all years in the period 2020-2050.

5.5. Effects of Sustainable Aviation Fuels

Now that is known what the minimum carbon mitigation must be in the carbon reduction scenarios to comply with goals; it now can be determined SAF alternative is suitable to fill the gap between the $\mathrm{CO_2}$ forecast and the carbon reduction scenarios.

5.5.1. Selection of alternative fuels

The comparison of fuels can be found in the B-tabs of the model. In tab B1, a list of eligible fuels can be found. These are extracted from a list from ICAO [54]. The conversion processes in this list comply with ASTM criteria, and the feedstocks are accepted by ICAO to be used for CORSIA carbon reduction. There has been chosen not to exclude first-generation fuels from this list to clarify the difference between first and second-generation fuels. The input data can be found in Table 5.3.

Life cycle assessment values are given by ICAO, which depicts Core LCA values and iLUC LCA values. The first refers to the actual $\mathrm{CO_2}$ that is emitted by the fuel, while iLUC refers to the indirect (or induced) Land Use Change. These values are high for, i.e. palm oil, because land area is extracted from food production to grow palm, which has a negative indirect effect on the environment and society. The combination of Core LCA and iLUC LCA gives a total Life cycle emissions factor for a CORSIA Eligible fuel (LSf), which is calculated in $gCO2e/MJ$. To give an idea of the quantity of these values, the LSf for fossil jet fuel is 89 gram of Carbon dioxide equivalent (CO2e) per Mega joule (a measure of energy content) (MJ).

Table 5.3: A list of CORSIA eligible fuels. LCA values retrieved from ICAO [54].

Conversion process	Fuel feedstock	Bearing	Core LCA value	iLUC LCA value	LSf (gCO2e /MJ)	Generation	ER	LSf (kgCO2e /kg fuel)
ATJ-SPK	Agricultural residues	Lignocellulosic	29.3	0	29.3	2G	2.120	1.04
ATJ-SPK	Corn grain	Lignocellulosic	55.8	22.1	77.9	1G	0.394	2.77
ATJ-SPK	Forestry residues	Lignocellulosic	23.8	0	23.8	2G	2.315	0.85
ATJ-SPK	Miscanthus	Lignocellulosic	43.4	-31	12.4	2G	2.720	0.44
ATJ-SPK	Sugarcane	Sugar/starch	24	7.3	31.3	1G	2.049	1.11
ATJ-SPK	Switchgrass	Lignocellulosic	43.4	-14.5	28.9	2G	2.134	1.03
FT-SPK	Agricultural residues	Lignocellulosic	7.7	0	7.7	2G	2.887	0.27
FT-SPK	Forestry residues	Lignocellulosic	8.3	0	8.3	2G	2.865	0.29
FT-SPK	Miscanthus	Lignocellulosic	10.4	-22	-11.6	2G	3.572	-0.41
FT-SPK	Municipal solid waste	Lignocellulosic	14.8	0	14.8	2G	2.635	0.53
FT-SPK	Poplar	Lignocellulosic	12.2	-5.2	7	2G	2.911	0.25
FT-SPK	Switchgrass	Lignocellulosic	10.4	-3.8	6.6	2G	2.926	0.23
HEFA-SPK	Corn oil	Oil	17.2	0	17.2	2G	2.549	0.61
HEFA-SPK	Palm fatty acid distillate	Oil	20.7	0	20.7	2G	2.425	0.73
HEFA-SPK	Palm oil - closed pond	Oil	37.4	39.1	76.5	1G	0.444	2.72
HEFA-SPK	Palm oil - open pond	Oil	60	39.1	99.1	1G	-0.359	3.52
HEFA-SPK	Rapeseed oil	Oil	47.4	24.1	71.5	1G	0.621	2.54
HEFA-SPK	Soybean oil	Oil	40.4	24.5	64.9	1G	0.856	2.30
HEFA-SPK	Tallow	Oil	22.5	0	22.5	2G	2.361	0.80
HEFA-SPK	Used Cooking Oil	Oil	13.9	0	13.9	2G	2.666	0.49
HFS-SIP	Sugar beet	Sugar/starch	32.4	20.2	52.6	1G	1.292	1.87
HFS-SIP	Sugarcane	Sugar/starch	32.8	11.3	44.1	1G	1.594	1.57

As discussed in section 2.3, the most attractive sustainable aviation fuel in a social perspective will be determined first. This is done by calculating the largest carbon reduction potential for each alternative. The overview can be found in tab B1 of the model.

The first step is to determine the global feedstock availability potential. Chuck et al. [23], Soubly et al. [111] and Swana et al. [116] give approximate availability for different feedstocks, which can be found in Table 7.1 (the results chapter). The source of specific numbers can be found in tab B1 of the model by checking the cell colours. For grown feedstocks, the feedstock yield per hectare is also important. Staples et al. [115] gives values for the feedstock per metric tonne SAF needed to produce the fuel.

The global feedstock availability potential divided by the feedstock per Mt SAF gives the SAF production potential. After that, the LSf within Table 5.3 is used, which states the life cycle emissions factor. With this factor, the CO_2 reduction potential per year can be calculated by using Equation 4.15.

5.5.2. Cumulative production

The first step to determine the most attractive fuel in a business perspective, is to determine future SAF production for each producer and specified by conversion process and feedstock used. In tab B2 of the model, an overview can be found of all current and future producers and their production trajectories. This includes diesel production because this fuel can be produced with the same conversion processes and feedstocks, which complement the experience curve theory.

Although this overview may not be fully complete or accurate (because producers may not communicate their entire strategy to the public), it gives an overview of production growth for the next 5 to 10 years. URL-sources related to the production numbers can be found in the columns at the end of the table in tab B2.

The fuel production quantities in tab B2 are summed to retrieve cumulative production values. Therefore, Equation 4.16 is used.

5.5.3. Price development

The next step is to use the cumulative production quantities to determine future prices. The different sources could not be compared easily due to different research methods and years in which the research was executed. Therefore, there has been chosen to apply a weighted average to determine the MSP that will be used in the analysis, assuming the most recent research will show the most accurate results. The oldest source (Staples et al. [114]) gets a weight of 1, while an extra year will receive an extra value 1, which ensures that Capaz et al. [19] and Vela-García et al. [127] both receive a weight of 7. The results can be found in Table 5.4. These weighted average prices will be used as input in the model (as $C_{i,2020}$ within Equation 4.17).

5.5.4. Quantities needed

In tab A5 of the model, there had been calculated previously how much CO_2 reduction need to be achieved to reach specific goals. Two goals have been mentioned: a 50% reduction of CO_2 emissions in 2050 compared to 2005, and a net-zero emissions scenario in 2050. In tabs A6 and A7 of the model, calculations of the following steps took place.

First, it is needed to calculate the SAF quantities needed to reach the CO_2 reduction goals of the two scenarios. By using the percentage of CO_2 reduction for each year and the expected total emissions after technological and operations improvements, the estimated total CO_2 reduction can be calculated. After that, the fuel alternatives' emissions reduction factor is used to determine the quantity of fuel needed for all fuel alternatives. This is done with the help of Equation 4.18.

These calculations for all years t from 2020 to 2050, and all fuel alternatives i, will create a fuel quantity road-map for both scenarios s. In tab A6 of the model, the 50% reduction scenario

Table 5.4: The minimum selling price of SAF according to various sources (USD/t)

Sustainable Aviation Fuel	Bann et al. [11]	Capaz et al. [19]	de Jong et al. [24]	ICAO [52]	ICAO [51]	Li et al. [73]	Pavlenko et al. [95]	Staples et al. [114]	Vela-García et al. [127]	Wei et al. [133]	Wang et al. [130]	Weighted average MSP
ATJ-SPK Agricultural residues	3342.21	1810.46	3384.80	2330.23	2500.00		3611.19		1514.20	2678.66	1512.57	2442.06
ATJ-SPK Corn grain	2210.39	1484.49		2077.23	2150.00		2512.78	2321.62		1841.47		2018.41
ATJ-SPK Forestry residues	3342.21	1810.46	2488.83	2396.80	2500.00		3611.19			2678.66	3482.43	2744.26
ATJ-SPK Miscanthus	3342.21	1810.46		2396.80	3250.00		3686.42			2678.66		2800.63
ATJ-SPK Sugarcane	1957.39	1484.49		2077.23	1900.00		2482.69	2075.39		2063.07		1983.75
ATJ-SPK Switchgrass	3342.21	1810.46		3062.58	3250.00		3686.42	3060.32		2678.66		2891.97
FT-SPK Agricultural residues	2000.00	1428.84	2591.32	1184.21	1050.00		2676.32			2398.40		1896.05
FT-SPK Forestry residues	2000.00	1428.84	1843.82	1552.63	1500.00		2676.32			2398.40		1949.95
FT-SPK Miscanthus	2000.00	1428.84		2578.95			2780.39			2398.40		2199.65
FT-SPK Municipal solid waste	1513.16				1550.00		1992.37					1729.06
FT-SPK Poplar	2000.00	1428.84		1552.63	1500.00		2780.39			2398.40	2155.09	1992.66
FT-SPK Switchgrass	2000.00	1428.84		1447.37	1500.00		2780.39			2398.40		1963.36
HEFA-SPK Corn oil				1375.17	1450.00					1250.32		1343.04
HEFA-SPK Palm fatty acid distillate				1375.17	1450.00		1478.50			1250.32		1383.68
HEFA-SPK Palm oil - closed pond		1528.35		1001.34	750.00		1508.68					1274.09
HEFA-SPK Palm oil - open pond		1528.35		1001.34	750.00		1508.68					1274.09
HEFA-SPK Rapeseed oil				1068.09	1150.00	1415.22				1102.19	917.02	1150.57
HEFA-SPK Soybean oil	1588.79	1612.52		1448.60	1450.00		1644.46			1447.83	1551.88	1542.55
HEFA-SPK Tallow	1415.22	1528.35		1535.38	1480.00					1250.32		1436.91
HEFA-SPK Used Cooking Oil	1214.95	1258.12	1501.77	1295.06	1300.00		1327.64			1250.32		1288.43
HFS-SIP Sugar beet			6045.50				5451.75			2373.58	2582.13	3928.79
HFS-SIP Sugarcane			6045.50				5451.75			2373.58	2582.13	3928.79

is used, while in tab A7, the net-zero scenario is calculated.

5.5.5. Cost NPV

After determining the fuel quantities needed to reach the scenario goals, it is needed to calculate the costs of implementing the alternative fuels. The prices calculated in tab B3 of the model (with the experience curve theory) are used with the fuel quantities per year calculated above.

The total cost per year is calculated with Equation 4.19. The cost reduction of acquiring fossil fuel is included in this equation. The latter is specified at 362.33 USD/ton due to a 36-month Moving Average forecast of jet fuel prices in table C5 of the model, which can also be seen in Figure 5.1.

5.6. Effects of Market-Based Measures

The next step in this analysis is to analyse the effects of Market-Based Measures on the overall outcome. The division of emissions within EU-ETS and/or CORSIA ensures savings related to the scenarios that have been described earlier.

5.6.1. CORSIA and EU-ETS

Without introducing SAF, TUI Aviation should have paid EU-ETS and CORSIA credits over all fuel and flights that they would have needed from 2020 to 2050, if these flights are relevant under the specific schemes (i.e. CORSIA is only for international flights and EU-ETS only for Intra-EER flights). However, the introduction of SAF ensures that there will be less net carbon emissions. Thus there will be a decrease in costs related to these two mandatory carbon mitigation schemes.

At first, it is essential to know what the carbon reduction per year should be for each scenario ($= EL_t - EG_{t,s}$). An earlier calculation has been used (from tabs A2 and A3 in the model) that already divided the carbon emissions into four categories (either none, EU ETS, CORSIA, or ETS+CORSIA). It is most important to start using SAF in the flights of the latter category

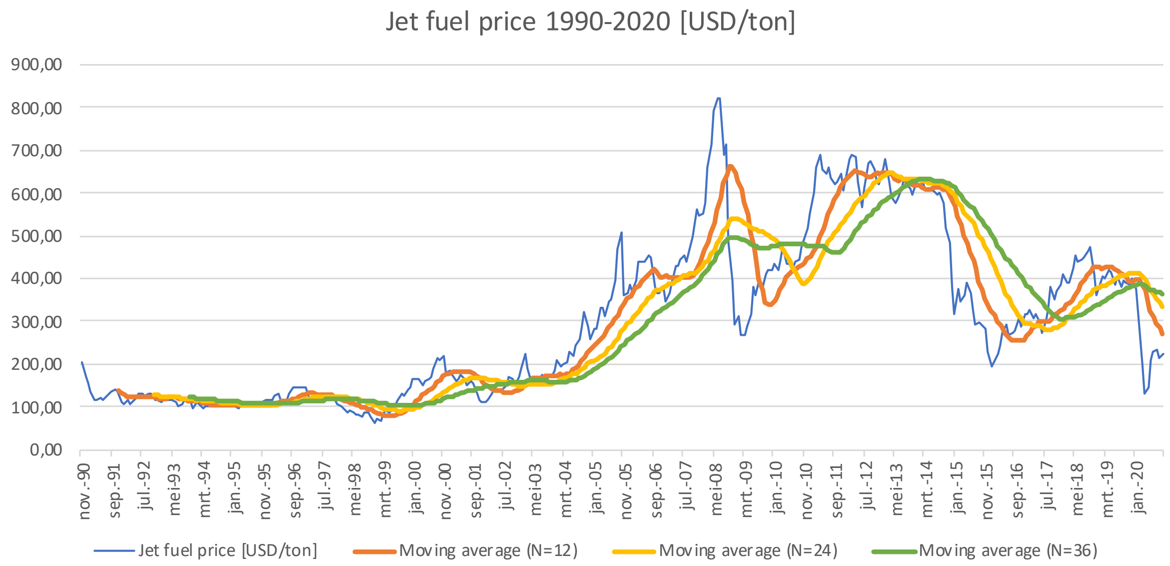


Figure 5.1: Fossil fuel price in 1990-2020 with a 12, 24 and 36 month Moving Average. Data retrieved from IndexMundi [59]

for financial reasons because this saves 50+15=65 USD/ton of CO_2 reduction. When SAF mitigates all ETS+CORSIA emissions for each year, operations can start using SAF in other categories, starting with the second most expensive one being EU ETS (50 USD). This will be followed by CORSIA (15 USD) and ”none” (0 USD).

The calculations at the bottom of tabs A6 and A7 of the model ensure that only the CORSIA emissions that overtake the 2019 baseline will be credited each year, and all EU ETS emissions will be credited each year. The yearly totals will be summed using an extra NPV, which results in an NPV cost reduction of 182.8 million USD for the 50% reduction scenario and 199.4 million USD for the net-zero scenario. This is equal for all fuel alternatives because the carbon reduction per year is the same for all alternatives.

5.6.2. Extra carbon offsets to reach goals

During this analysis, it seemed that some SAF alternatives did not have enough carbon mitigation per metric tonne of SAF to reach the goals fully.

The left-over carbon emissions that need to be mitigated to reach the goals need to be offset via voluntary carbon offsetting. These carbon credits cost approximately 10 USD per metric tonne of CO_2. Assuming TUI Aviation needs to offset all carbon emissions that limit them from reaching their goals, these will be credited in this model.

6

Verification and Validation

This chapter will focus on the verification and validation of the model. It will start with a general introduction in section 6.1, followed by the verification in section 6.2 and the validation in section 6.3. The chapter finishes with a sensitivity analysis in section 6.4.

6.1. Introduction

In the previous chapter, a model had been created to determine the future expected demand, the resulting CO_2emissions, the carbon efficiency improvements of technology and operations, the scenarios to implement SAF, and the cost of SAF alternatives, taking into account the market-based measures. This resulted in an extensive computerised Microsoft Excel model that contains 15 tabs and countless calculations and data. To make sure that the model is designed well and the outcomes are reliable, it is needed to perform verification and validation before making conclusions.

Oberkampf et al. [92] describe the steps that need to be taken towards the verification and validation of a computerised model. They describe verification as the process of determining that a model implementation represents the developer's conceptual description of the model and the solution to the model accurately. Validation is described as the ”process of determining the degree to which a model is an accurate representation of the real world from the perspective of the indented use of the model” [92].

The conceptual model in Figure 6.1 is equal to the conceptual model used in this thesis, which can be found in Figure 6.2. As this conceptual model's basis comes from Air Transport Action Group [4], the model qualification (to match the conceptual model with reality) has already partially been performed by ATAG. Another review has taken place by the author of this thesis to determine whether this model fits into the case study of TUI Aviation, which it does. The additions to the original ATAG-model are sub-processes within the SAF effects and MBM effects, and these do not undermine the initial model qualification.

The computerised model is the model made for this thesis (CO_2 and SAF forecast thesis.xlsx). Model verification is needed to verify whether the Excel-based (computerised) model fits the conceptual model accurately. This is a continuous process during the development and programming of the Excel-based model. Every little step in the development phase (toward Excel cell level) contained a certain form of verification, for example, by checking whether the formulas resulted in sensible outcomes. This can be found in section 6.2.

The last part is to compare the computerised model with reality, which is done by model validation. The computer simulations that result from the computerised model need to represent outcomes in reality. This process happens after the development and programming of the Excel-based (computerised) model. This can be found in section 6.3.

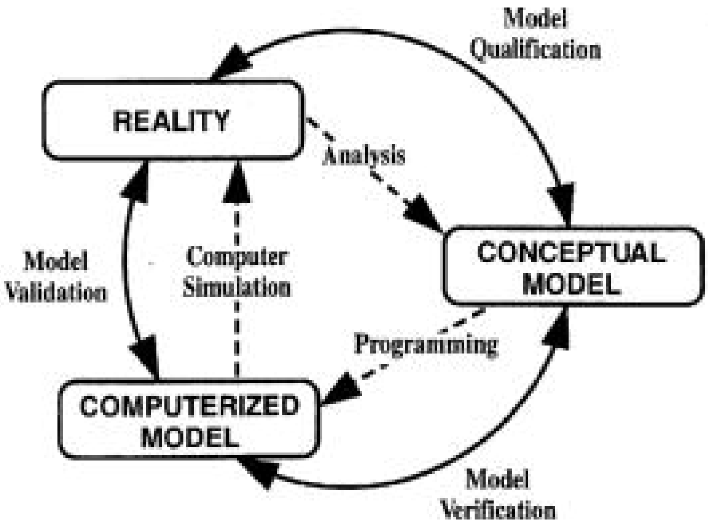


Figure 6.1: Phases of modelling and simulation and the role of verification and validation. Adapted from Schlesinger [102]

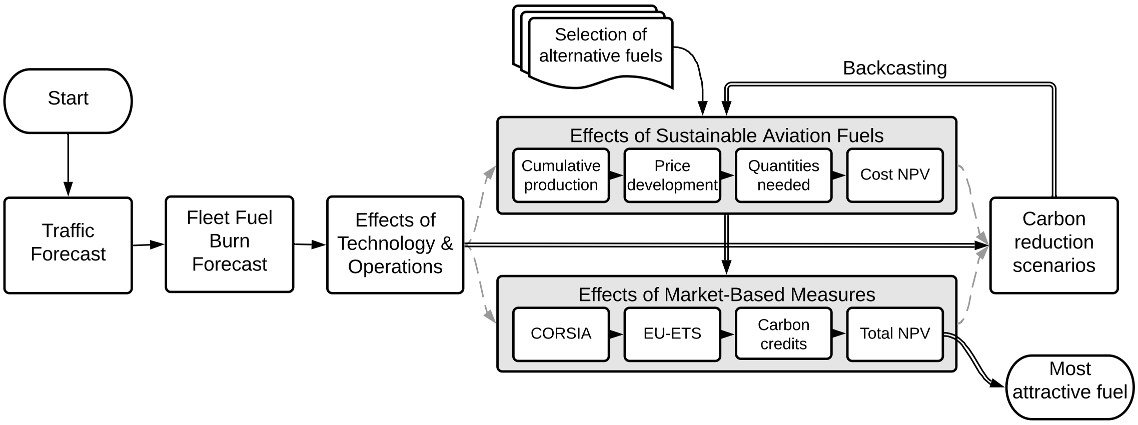


Figure 6.2: Conceptual model

6.2. Verification

6.2.1. Model components

The first thing that needs to be verified is whether all conceptual model components are included in the computerised model. In Table 6.1, the link between the conceptual model and computerised model components are stated. With this, it is concluded that all relevant components of of the conceptual model are included in the computerised model.

Table 6.1: Model verification of conceptual model steps and the computerised (Excel-based) model

Conceptual Model	Computerised Model
Traffic Forecast	A1. Demand
Fleet Fuel Burn Forecast	A2. Fuel Burn CO_2
Effects of Technology & Operations	A3. CO_2 improvements
Carbon Reduction Scenarios	A5. Scenarios
Selection of alternative fuels	B1. Fuels
Cumulative Production	B3. Cum. Production and Price
Quantities needed	A6. 50% reduction & A7. Net-zero
Cost NPV	A6. 50% reduction & A7. Net-zero
CORSIA	A6. 50% reduction & A7. Net-zero
EU-ETS	A6. 50% reduction & A7. Net-zero
Carbon Credits	A6. 50% reduction & A7. Net-zero
Total NPV	A6. 50% reduction & A7. Net-zero
Most attractive fuel	A6. 50% reduction & A7. Net-zero

In the conceptual model, the effects of alternative fuels and the addition of emissions reductions (market-based measures) are the last steps before reaching the goal. However, this research was performed to measure the effects of alternative fuels to achieve a predefined goal (the two scenarios). Therefore, the goal is determined first in the computerised model. The effects of alternative fuels and market-based measures are backcasted against the goal, as can be seen in Figure 6.2.

6.2.2. Unit testing

Besides the availability of all conceptual model components in the computerised model, it is also needed to test individual units of the model. Most important is to verify whether the coding in the model is correct. All units are tested against the following criteria:

- **Quantitative model**: The model is quantitative; therefore, all results need to be expressed in numbers (no string variables).

- **Correctness**: The model uses mathematical expressions and formulas to analyse and compare the costs and emissions. The application and use of these formulas have to be checked for correctness.

- **Unit equality**: The units of data need to be the same at all times, for instance, litres for volume, kg (or tonne) for weight, and USD for monetary values. Sometimes, research gave values in other units (such as gallons instead of litres), these have been converted before being added to the model.

- **Time**: The time steps of scenarios and all other time-related data need to be the same (in years), and all time-dependent variables will be calculated for all periods in 2020-2050.

These criteria will lead to the following unit testing results in Table 6.2. Some parameters could not be tested on Time correctness, while these parameters are not time-dependent. Therefore, ”N/A” is stated at Time-dependent for these parameters.

Table 6.2: Unit testing of parameters in computerised model

Model worksheet	Parameter	Quantitative	Correctness	Unit	Time
A1. Demand	Recovery year	Y	Y	N/A	Y
	RPK	Y	Y	Y	N/A
	30 year CAGR	Y	Y	Y	N/A
	Demand (t)	Y	Y	Y	Y
A2. Fuel burn CO_2	CO_2	Y	Y	Y	N/A
	CO_2 / RPK	Y	Y	Y	N/A
	CO_2 (t)	Y	Y	Y	Y
A3. CO_2 improvements	Tech. Improvement %	Y	Y	Y	N/A
	Oper. Improvement %	Y	Y	Y	N/A
	CO_2 (t)	Y	Y	Y	Y
A4. SAF Quota	Quota (i,t)	Y	Y	Y	Y
	Quota (t)	Y	Y	Y	Y
	Fuel share (i)	Y	Y	Y	N/A
A5. Scenarios	Mitigation start level	Y	Y	Y	N/A
	Mitigation start year (t)	Y	Y	N/A	Y
A6. 50% reduction	Discount rate	Y	Y	Y	N/A
	Fossil fuel price	Y	Y	Y	N/A
	CORSIA cost	Y	Y	Y	N/A
	EU-ETS cost	Y	Y	Y	N/A
	SAF needed (t)	Y	Y	Y	Y
	NPV of SAF costs	Y	Y	Y	N/A
	NPV of MBM savings	Y	Y	Y	N/A
A7. Net zero	*Same as A6 above*				
B1. Fuels	Core LCA value	Y	Y	Y	N/A
	iLUC LCA value	Y	Y	Y	N/A
	LSf	Y	Y	Y	N/A
	ER	Y	Y	Y	N/A
	Minimum selling price	Y	Y	Y	N/A
	CO_2 reduction potential	Y	Y	Y	N/A
B2. Producers	Production (t)	Y	Y	Y	Y
B3. Cum. Production and price	Average MSP	Y	Y	Y	N/A
	Production (t)	Y	Y	Y	Y
	PRi	Y	Y	Y	N/A
	Cost (t)	Y	Y	Y	Y

6.3. Validation

As has been discussed in section 6.1, validation is needed to check whether the computerised model's outcomes represent reality. Where quantitative checks were mainly used in verification (unit testing), invalidation the qualitative checks are more important. The main questions are whether the model is the right model for the job and whether the literature and data used reflect reality.

6.3.1. Acceptance testing

In Table 6.3, there can be seen that all sub-questions are included in the model. The sub-questions relate to the reality; the research gaps for which an answer needed to be found.

Table 6.3: Model validation of sub-questions (reality) and the computerised (Excel-based) model

Sub-question	Computerised Model
What stakeholders in commercial aviation are involved and what are the regulations, policies and goals regarding SAF that they have set?	A4. SAF quota & C3. Offtake & C4. Airline goals
What is the current traffic forecast, taking the current COVID-19 crisis into account?	A1. Demand
What are the resulting emissions from the traffic forecast,	A2. Fuel Burn CO_2
taking the effects of technology and operations into account?	A3. CO_2 improvements
What is the advised timeline of carbon mitigation, which will be achieved by SAF introduction and adoption?	A5. Scenarios
What are attractive SAF alternatives in a social and business perspective,	A6. 50% reduction & A7. Net-zero
taking market-based measures into account?	A6. 50% reduction & A7. Net-zero
What SAF innovations are currently in development or on the market?	B1. Fuels
What SAF innovations comply with selection criteria regarding technological feasibility, cost/benefit, stakeholder acceptability, and timescale of adoption?	B3. Cum. Production and Price
What are attractive SAF alternatives in a social and business perspective, taking market-based measures into account?	A6. 50% reduction & A7. Net-zero

Most important for TUI Aviation is to have a dashboard to (1) compare different SAF alternatives, so a decision can be made which alternative suits the company best in terms of costs and technological readiness, and (2) what timeline of adoption could be used to reach specific goals in the future. The latter is essential to create a SAF implementation strategy, TUI Aviation needs to decide when they want to start with the introduction of SAF, and what the quantities per year (and growth of these quantities) should be to reach their goals.

Based on these points, the computerised (Excel-based) model fulfils these requirements and is the right model for the client. Therefore, the model is validated in terms of acceptance testing.

6.3.2. Data validation

The next important aspect of validation is to validate the literature and data used in the model. The model contains a lot of information that is assumed to be reliable, but some are more reliable than others. Each main data component is stated in Table 6.4, that states the reliability of sources, the usability of the data, and comments when necessary.

Table 6.4: Overview of data validation

Data components	Reliability of sources	Usability of data	Comments
COVID-19 recovery year	No papers, only news articles	Good	Used many sources to conclude with a reliable estimate
TUI Demand data	Reliable, analysis with company data	Very good	Data verified by third party
TUI CO_2 data	Reliable, analysis with company data	Very good	Data verified by third party
Compound Annual Growth Rates	Reliable source by reputation	Good	ICAO is a respected UN institution
Efficiency improvement percentages	Seems reliable, but different data found	Good	Minimums chosen to prevent overestimation of carbon reduction
SAF governmental quota	Hard to find data	Fair	Many governmental intentions, this list will extend over the years
Fossil fuel price	Reliable source with 30 year price development	Good	Historical prices don't necessarily estimate future prices (until 2050)
Market-based Measure costs	Reliable source by reputation	Good	Costs can change in the future
SAF characteristics	Reliable source by reputation	Good	Characteristics must be used within CORSIA carbon reporting
SAF minimum selling prices	Many sources, but different outcomes	Fair	Used a weighted average with many different sources (sort of ”wisdom of the crowd”)
SAF production potential	Reliable sources, but hard to find data	Fair	Used different sources for different SAFs, methodologies of sources may differ
SAF production quantities per year	No papers, only news articles and producer websites	Poor	Producers may keep their production targets confidential, overview may not be complete
Process ratio (PR_i)	Reliable source	Fair	Generic numbers (no SAF) in sources, maximums chosen to prevent overestimation of price reduction

6.4. Sensitivity Analysis

In Appendix D, a sensitivity analysis of the model can be found. The procedure is explained in the attachment.

The general conclusion is that the discount rate (set at 10%) is the most sensitive parameter in the model. Changing this variable to 5% gives NPV results that are 200% more expensive. This is because most costs occur at the end of the timeline (towards 2050) and a discount rate has the largest influence on costs and/or income in the far future.

The Process Ratio (used in the experience curve process to determine future prices) is a sensitive parameter. Changes in NPV only happen in a few SAF alternatives, because some do not have any cumulative production data. Changes in cumulative production are needed to change prices over time.

Another critical variable is the weighted average Minimum Selling Price (MSP). This is not a surprising result, because the NPV of SAF implementation mainly consists of fuel prices. Although many documentation is used and all fuels have multiple sources, there was still no clear outcome of what acceptable MSPs could be. A weighted average has eventually been used to retrieve data to apply in the model, as explained in subsection 3.4.5. Future users need to take into account that MSP modifications may improve the results of the model.

One of the most interesting conclusions is that the Carbon Mitigation Start Level is sensitive in one direction (only an NPV increase). The model default starts with 1% carbon reduction in 2023; thus, the sensitivity analysis is done with 0.5% and 1.5%. Both with a 50% increase and 50% decrease of the start level, the result is that the NPV increases, resulting in more costs. Apparently, there is a (local) optimum that has lower costs.

One other conclusion is that the fuel FT-SPK from Municipal Solid Waste is still the cheapest option after almost all sensitivity steps. The only time that another fuel was cheaper was when the Process Ratio of all fuels was set to 1.0. In contrast, all HEFA-SPK fuels already had 1.0 by default (a further increase of this variable is technically not possible). In this scenario, HEFA-SPK from Used Cooking Oil was cheaper than the fuel made from MSW.

7

Results

7.1. Traffic Forecast

In tab A1 of the computerised model, the resulting traffic or demand forecast can be found. The user can change the expected COVID-19 recovery year (set at 2023) and the CAGR from ICAO [53]. The latter is specified per market. It is also possible for the user to use a custom CAGR (in the yellow cells of in the model) that overwrites the default one. With the default CAGR, the expected forecast for 2023 (the recovery year) is 79,073 million RPK, which grows to 181,278 million RPK in 2050.

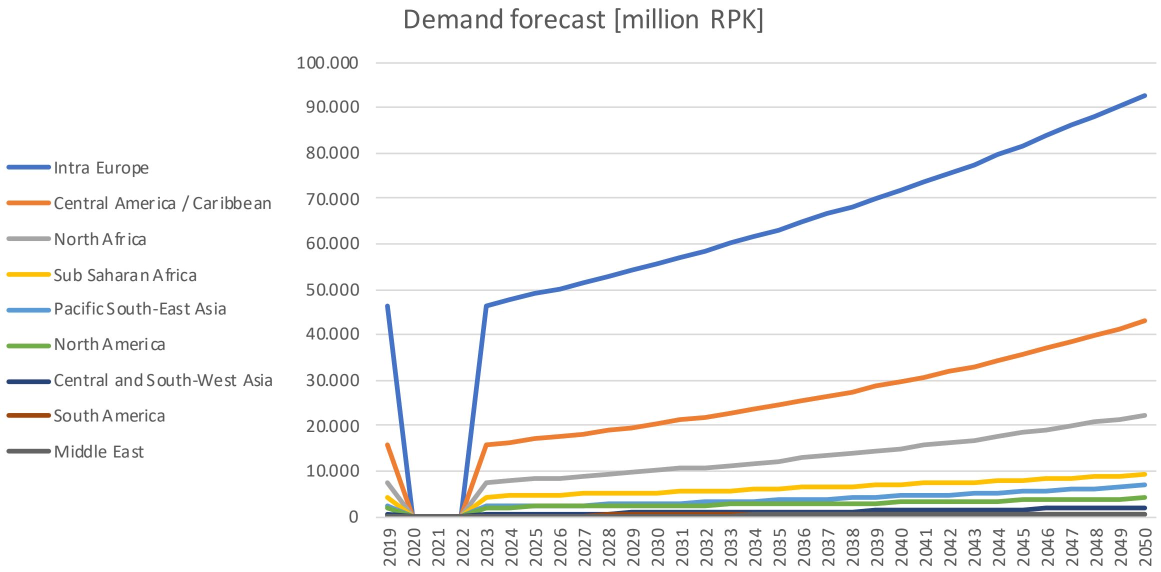


Figure 7.1: Demand forecast for TUI Aviation in 2020-2050 in million Revenue Passenger Kilometers

A resulting graph can be found in Figure 7.1. The *Intra Europe* market is the largest, with holiday destinations in, e.g. Spain, Greece and Turkey, with more than 90,000 million RPK expected in 2050. The *Central America / Caribbean* market follows with more than 40,000 million RPK. All markets except Intra Europe are markets between Europe and the other continent, for example, *Europe <-> Central America / Caribbean*, because all TUI operations originate in Europe. For simplicity reasons, the name *Europe* is excluded from all other market names.

7.2. Fleet Fuel Burn Forecast

In tab A2 of the model, the traffic forecast is converted to a CO_2 emissions forecast. To give a visual explanation of EU-ETS and CORSIA relevance among flights, a distribution can be seen in Figure 7.2.

In the "Business-as-Usual" or "No-action" scenario, the carbon emissions of TUI Aviation will grow to 12.07 Mt of CO_2 per year in 2050. CORSIA relevant flights will be 8.78 Mt (yellow and grey), while EU-ETS will be 5.46 Mt (yellow and orange). Around a fourth of the emissions (blue) are caused by flights that are not eligible to one of these obligatory carbon mitigation schemes, so there will not be any carbon costs for these flights in the foreseeable future.

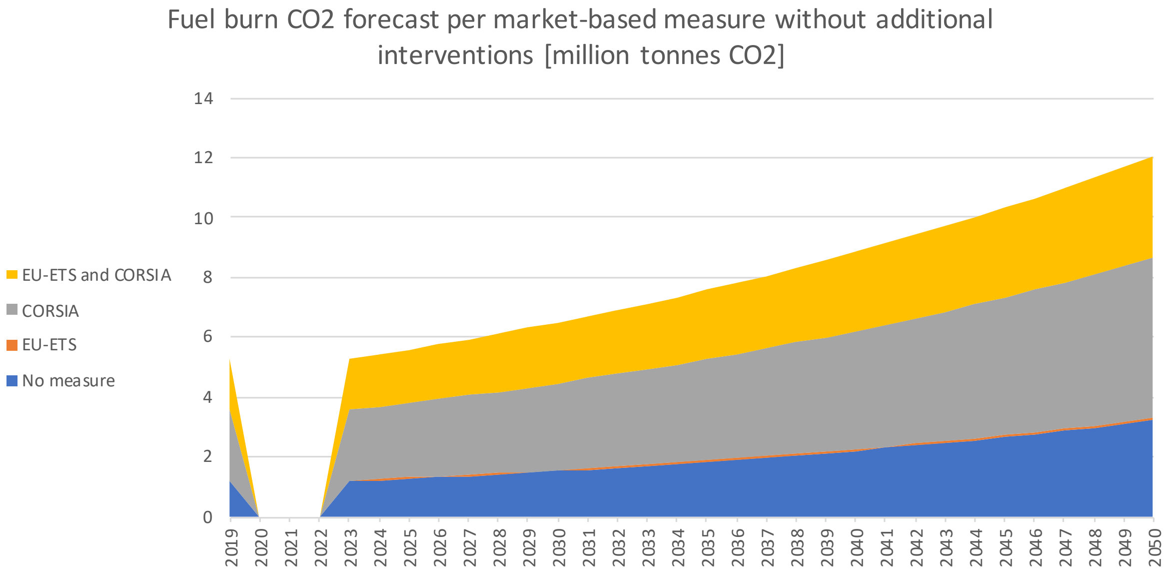


Figure 7.2: CO_2 forecast for TUI Aviation in 2020-2050 in million metric tonnes of CO_2 per MBM

7.3. Effects of Technology and Operations

The next step is to include efficiency improvements from technology and operations in the CO_2 emissions forecast. This can be found in tab A3 of the model. In Figure 7.3, the resulting graph can be found. In 2050, a 3.23 million ton technology improvement and a 0.71 Mt operational improvement are expected. Subtracting these from the "No Action" scenario (12.07 Mt) results in a new CO_2 emission forecast of 8.13 Mt (the blue area in Figure 7.3).

7.4. Carbon reduction scenarios

As has been discussed in section 5.4, two carbon reduction goals have been formulated; a 50% reduction of CO_2 emissions in 2050 compared to 2005, and a net-zero emission goal. The model calculated two carbon reduction scenarios related to these goals in tab A4. Most important is the annual growth rate of carbon mitigation. A graphical representation can be seen in Figure 7.4 with reduction start level 1.0% in the start year 2023.

The 50% reduction scenario requires a maximum of 2.11 Mt of CO_2 in 2050. Starting in 2023 with 1% reduction requires a 17.3% annual growth factor in carbon mitigation. The net-zero scenario will lead to no emissions in 2050, using a start in 2023, and 1% carbon reduction requires an 18.6% annual growth factor in carbon mitigation.

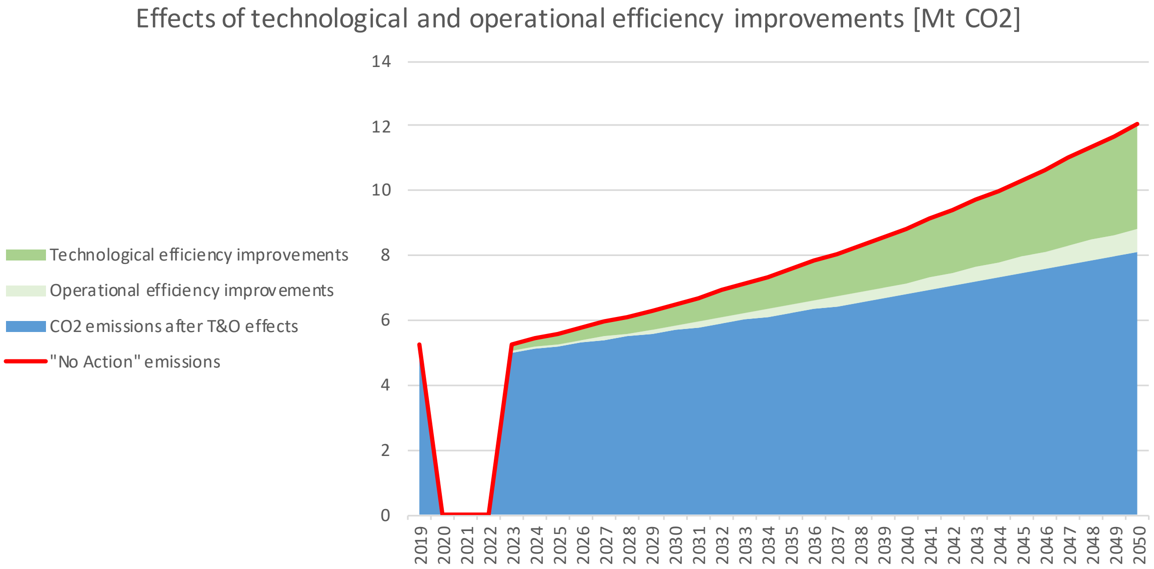


Figure 7.3: The effects of technological and operational efficiency improvements on the fuel burn CO_2 forecast of TUI Aviation

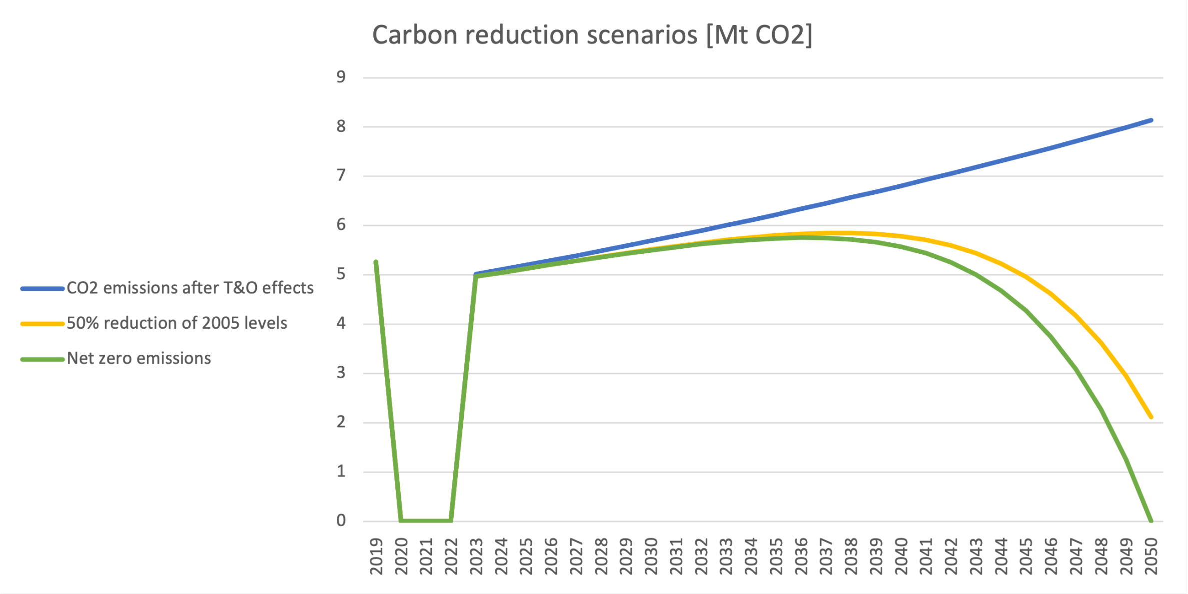


Figure 7.4: Scenario forecast for TUI Aviation in 2020-2050

7.5. Effects of Alternative Fuels

7.5.1. Preferred Sustainable Aviation Fuel for society

In subsection 4.4.5, the calculations were stated that determine the SAF alternative with the most carbon reduction potential. These calculations give the following results in Table 7.1. Within the second-generation fuels, the FT-SPK process with Municipal Solid Waste is the most promising alternative with more than 300 million tonnes of CO_2 reduction potential per year. Fuels using the sugarcane feedstock are also promising, but these are first-generation fuels that can conflict with food availability due to induced land-use change.

Table 7.1: SAF production potential and cost per mitigated tonne of CO_2 in 2020, sorted by CO_2 reduction potential

Sustainable Aviation Fuel	Feedstock availability potential [Mt/yr]	Feedstock yield [ton/ha/yr]	Feedstock per Mt SAF [Mt]	SAF potential [Mt/yr]	CO_2 reduction potential [Mt/yr]	Cost per ton CO_2 reduction	Generation
FT-SPK Municipal solid waste	960.0		8.35	115.0	**303.0**	409.59	2G
FT-SPK Miscanthus	152.6	24.0	5.09	30.0	**107.2**	433.85	2G
FT-SPK Agricultural residues	330.0		9.43	35.0	**101.0**	431.67	2G
FT-SPK Forestry residues	290.0		8.92	32.5	**93.1**	453.69	2G
ATJ-SPK Miscanthus	152.4	24.0	5.08	30.0	**81.6**	790.75	2G
ATJ-SPK Forestry residues	290.0		8.92	32.5	**75.2**	904.66	2G
ATJ-SPK Agricultural residues	330.0		9.43	35.0	**74.2**	845.44	2G
FT-SPK Switchgrass	64.5	20.0	5.37	12.0	**35.1**	448.91	2G
HEFA-SPK Used Cooking Oil	25.0		2.03	12.3	**32.8**	239.43	2G
ATJ-SPK Switchgrass	64.5	20.0	5.37	12.0	**25.7**	1050.65	2G
FT-SPK Poplar	16.0	18.0	2.04	7.8	**22.8**	461.16	2G
HEFA-SPK Tallow	13.5		2.03	6.6	**15.7**	333.28	2G
HEFA-SPK Corn oil	3.2		2.03	1.6	**4.0**	271.86	2G
HEFA-SPK Palm fatty acid distillate	0.7		2.03	0.3	**0.8**	302.54	2G
ATJ-SPK Sugarcane	1877.1	70.7	15.30	122.7	**251.4**	651.03	1G
HFS-SIP Sugarcane	1877.1	70.7	14.86	126.3	**201.4**	2056.69	1G
ATJ-SPK Corn grain	1017.7	5.5	4.42	230.1	**90.7**	3472.12	1G
HFS-SIP Sugar beet	275.0	69.1	10.59	26.0	**33.5**	2536.97	1G
HEFA-SPK Soybean oil	41.9	2.5	2.03	20.6	**17.6**	1043.08	1G
HEFA-SPK Palm oil - closed pond	48.4	15.7	2.03	23.8	**10.6**	1406.17	1G
HEFA-SPK Rapeseed oil	22.6	2.2	2.03	11.1	**6.9**	805.63	1G
HEFA-SPK Palm oil - open pond	48.4	15.7	2.03	23.8	**-8.5**	-1740.31	1G

The most attractive alternative per monetary value spent is defined in the column "Cost per ton CO_2 reduction". FT-SPK with Municipal Solid Waste scores well here too, with just over 409 USD per ton CO_2 reduction. However, HEFA-SPK process fuels have lower costs, with the minimum being the Used Cooking Oil feedstock with 239 USD per ton CO_2 reduction. However, the limited availability of HEFA-SPK feedstock in the world limits the total CO_2 reduction potential for these alternatives. Please note that the weighted average MSP is used for these conclusions, without considering the experience curve effects.

7.5.2. Cumulative production forecast

In subsection 5.5.2, the cumulative production of SAF alternatives has been calculated. This results in the following production forecast in Figure 7.5.

The figure gives a clear view of several alternatives' production forecast, with HEFA-SPK from Used Cooking Oil and Tallow being the most produced fuels in the coming years. This could be due to the maturity of the HEFA production process. In section 3.5, there has been discussed that the HEFA technology is mature and therefore easy to implement at the moment, while other production processes and technologies are still in development.

In total, we can expect more than 13 million tonnes of renewable fuels to be produced in 2025, while current production is almost 5 Mt. According to this overview, this will increase to 17 Mt in 2030.

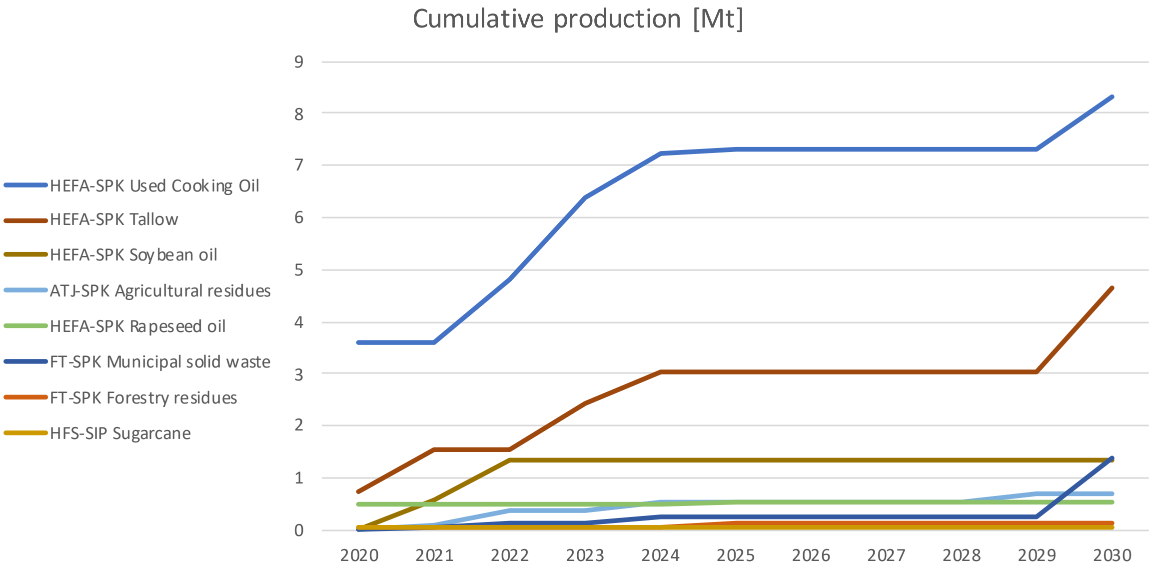


Figure 7.5: Cumulative production of fuel alternatives (in Mt), only showing the alternatives with known production quantities and including diesel fuels

One major drawback of this overview is that not all production increases are included, especially in the period 2025-2030. Production increase information has to be publicly available, and some producers may not have plans yet for the mid- to long-term. Therefore, we should see the production quantities as the minimum quantity and the resulting price (after experience curve theory) to be the maximum price, still giving possibilities to have lower prices if the production increases more than indicated.

7.5.3. Price after experience curve effects

The experience curve theory was used to determine future prices of SAF alternatives. The cumulative production of these alternatives was used as input in this analysis. Using a PR_i of 1 for HEFA fuels and 0.9 for other fuels (as has been discussed in section 3.5) results in Figure 7.6.

This graph shows that HEFA fuels have a constant price between 2020 and 2030 (due to the $PR_i = 1$), while others have a decreasing price. One of the outstanding alternatives is FT-SPK of Municipal Solid Waste, starting at 1729 USD/ton in 2020 and ending at 980 USD/ton in 2030. ATJ-SPK with Agricultural Residues also decreases proportionally, with 2442 USD/ton in 2020 and 1521 USD/ton in 2030.

7.5.4. SAF quantities needed

Not all SAF alternatives have the same carbon reduction power per ton fuel. Therefore, each SAF alternative requires another offtake quantity to reach a certain carbon mitigation level. The results for the net-zero scenario can be found in Figure 7.7.

The interrupted line gives the total fuel quantity (either fossil or alternative fuel) needed for future expected TUI Aviation operations. Some fuels are above the interrupted line toward 2050, meaning that the carbon reduction of these fuels does not suffice and external carbon reduction via voluntary offsetting (i.e. planting trees) is required.

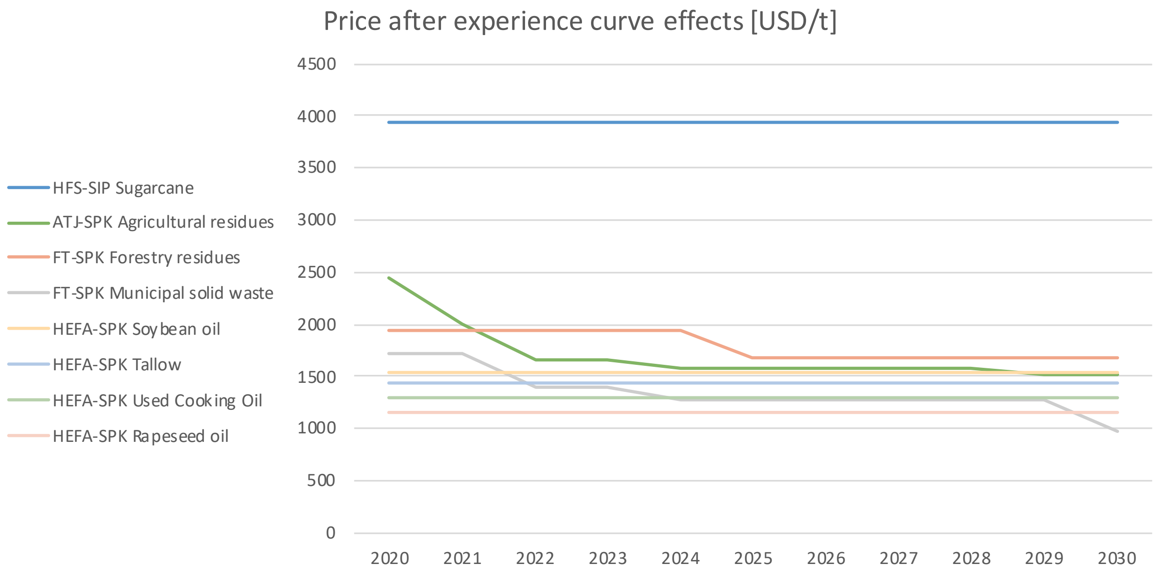


Figure 7.6: Cost of fuel alternatives after experience curve effects (in USD/ton)

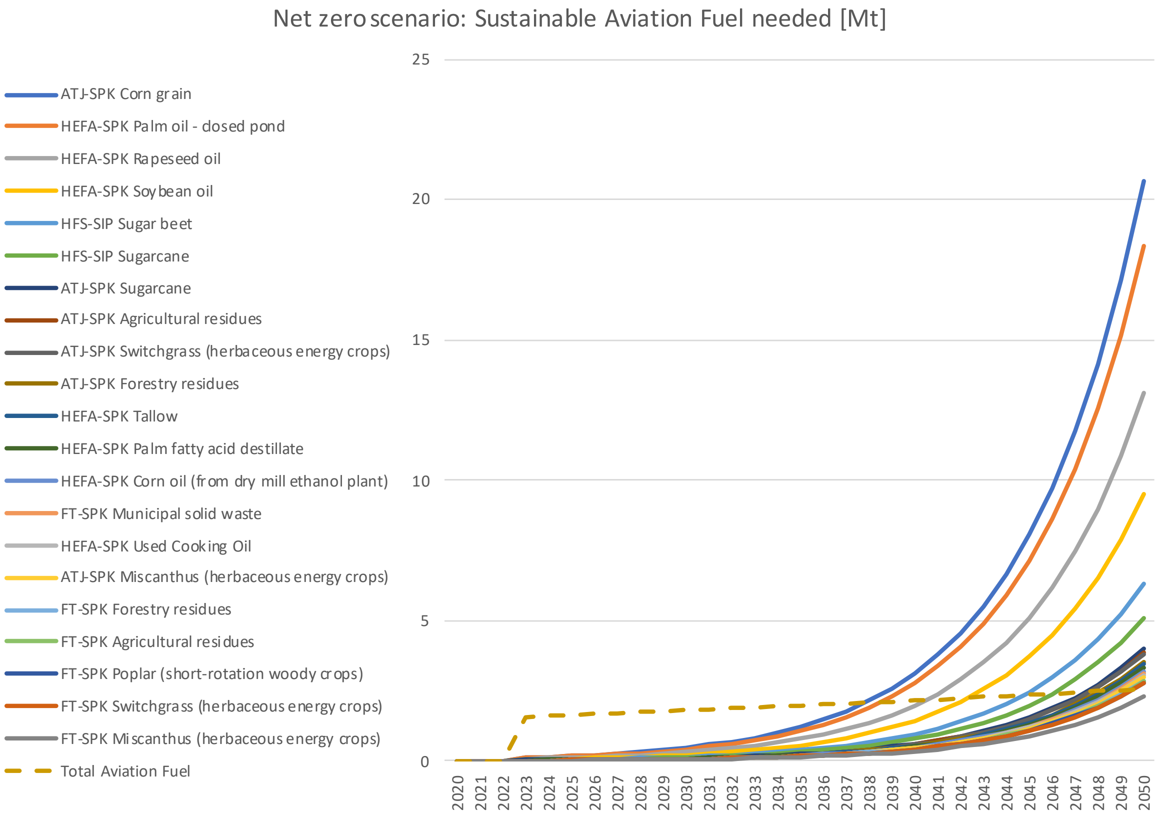


Figure 7.7: Fuel quantities needed in the net zero scenario

7.5.5. Net Present Value

After determining the offtake quantities of each SAF alternative, these offtake quantities per year could be used with the future prices to calculate the implementation costs per year. The cost reduction of fossil fuel purchasing is included in this calculation.

The eventual NPV of all SAF alternatives can be found in tabs A6 and A7 of the model. FT-SPK fuel made from Municipal Solid Waste scores best, with 878 million USD NPV costs for the 50% reduction scenario and 1074 million USD for the net-zero scenario. However, in the latter scenario, 120% of the fuel offtake needs to be SAF, which is not possible. This means that additional offsetting is needed using voluntary offsetting programs (climate compensation).

7.6. Effects of Market-Based Measures

In the last step, the cost reductions of CORSIA and EU-ETS are included in the NPV. Fewer emissions ensure fewer costs that relate to obligatory carbon mitigation schemes. During this analysis, it seemed that some SAF alternatives did not have enough carbon mitigation per metric tonne of SAF to reach the goals that have been set fully. Therefore, the addition of voluntary offsetting programs is required.

In the 50% reduction scenario, the tipping point is a 67% reduction in carbon emissions compared to fossil fuel. This means that any fuel that scores worse than 67% does not reach the goal in 2050 without additional measurements. This means that 11 out of 22 fuels do not fully comply.

In the net-zero scenario, it seems logical that a fuel needs to have a 100% carbon reduction compared to fossil fuel. Otherwise, the left-over carbon emissions will ensure that the net-zero emissions goal could never be met. Only the FT-SPK Miscanthus fuel is eligible in this scenario (due to a net decrease in emissions by using the fuel; -113% compared to fossil fuel). A mention is needed that this fuel is only theoretically possible, no production plans have been mentioned yet (thus no production values in tab B2. Producers in the model). The final outcome will be to extract the MBM-savings from CORSIA and EU-ETS from the NPV calculated earlier and add extra costs that need to be made if goals could not be met with the specific fuels.

An overview of the complete NPV for the net-zero scenario can be found in Figure 7.8. The cheapest alternative, including the Market-Based Measure savings, is FT-SPK with Municipal Solid Waste. This will cost TUI Aviation 874.9 million USD for the net-zero scenario (695.3 million USD for the 50% reduction scenario).

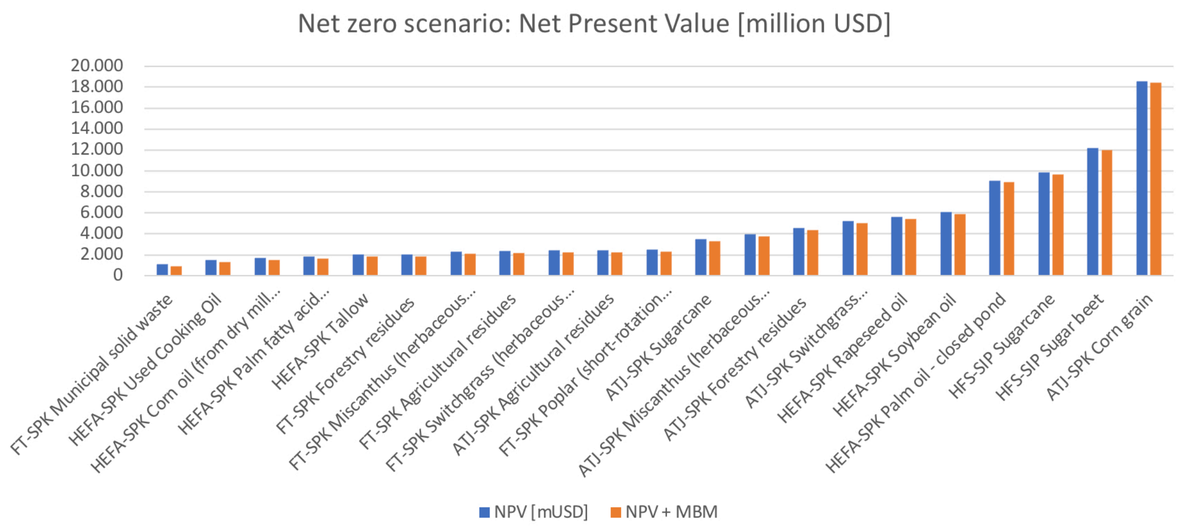


Figure 7.8: NPV (costs) including MBM savings for net zero scenario

7.7. Conclusion

The analysis gives the Total NPV as a result for all 22 SAF alternatives that are ASTM certified (and thus technically ready to use). However, not all of these alternatives have a cumulative production planned in the coming years. Therefore, 14 SAF alternatives need to be excluded for now. Besides that, some SAF alternatives do not comply with stakeholder policies and goals. As discussed in section 3.1, fuels may not be a first-generation fuel, because these feedstocks interfere with food production. This eliminates a further 3 SAF alternatives from the selection. This leaves five eligible fuels for this research. The overview of these fuels can be found in Figure 7.9.

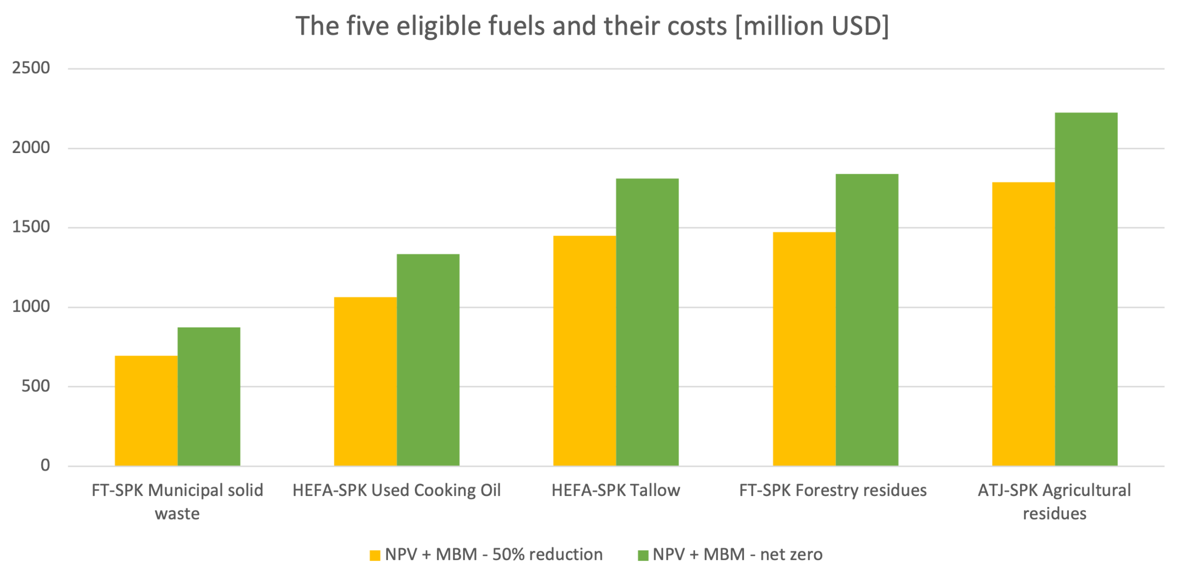


Figure 7.9: The resulting fuels that could be implemented in TUI Aviation operations

8

Conclusions and Recommendations

8.1. Conclusion

This research aimed to find potential attractive SAF alternatives in a social and business perspective. Doing a case study at TUI Aviation made it possible to work with a real-life situation and adapt knowledge and data into scenarios.

The first sub-question was to determine stakeholders and their regulations, policies and goals. Some international organisations have set guidelines to limit carbon emissions in commercial aviation. The two leading organisations are ICAO, part of the United Nations, and the European Union. The first implemented the CORSIA carbon mitigation scheme, ensuring that international aviation will have a climate-neutral growth from 2019. All emissions above that baseline year need to be offset by using SAF or acquiring carbon credits from other sectors. The latter introduced the EU-ETS offsetting scheme which requires airlines to pay for carbon emissions from flights within the European Economic Area. They require that biofuels need to emit at least 65% less carbon than fossil fuels. Some national governments have set SAF quota to stimulate the sector, the Nordic countries being the most innovative by requiring up to 30% use of SAF in 2030. Airlines typically follow one out of two common goals; most of them limit the carbon emissions in 2050 by 50% compared to 2005 levels. Some airlines are more venturous and strive toward net-zero emissions in 2050. Both scenarios have been used in this research.

To perform the case study at TUI Aviation, a traffic forecast was needed to predict what future demand and resulting CO_2 emissions would be. Compound Annual Growth Rates are used to determine the demand growth per market. The average total CAGR for TUI is estimated at 3.06% per year. Due to the COVID-19 pandemic, an extra tool had to be implemented to deal with this crisis. Desk research concluded that 2023 would be a recovery year that demand would be back at 2019 levels. Starting from then, the demand grows with 3.06% per annum. The 79 million Revenue Passenger Kilometres in 2019 will ultimately result in 181 million RPK in 2050.

These demand numbers have been used to determine the CO_2 emissions related to those operations. In a Business-as-Usual scenario, this would result in 12.1 million metric tonnes of carbon dioxide in 2050, while this was 5.3 million tonnes in 2019. However, some external factors will ensure a lower growth in carbon emissions than this forecast. Technological efficiency improvements would result in a 1% decrease per year, while operational efficiency results in a total of 6% improvement in the coming 30 years. This results in a carbon forecast of 8.1 million tonnes of carbon in 2050.

The next sub-question was to create an advised timeline of carbon mitigation. Considering the two scenarios described above, these two timelines have been calculated using an exponential function. In the default values, the company will start with 1% carbon reduction in 2023, and this reduction percentage will grow exponentially by either 17.3 or 18.6% per year, depending on the scenario involved. This timeline fulfils the now-known upcoming SAF blending mandates set by national governments.

The next step was to provide an initial set of SAF alternatives. ICAO provided a list of CORSIA eligible fuels and their characteristics which also comply with regulatory standards (ASTM certification). Some did not pass all requirements because they were considered a first-generation fuel, limiting carbon reduction and interfering with food production. To give a clear overview of the differences between first and second-generation fuels, there has been chosen to include all of those. This resulted in a list of 22 fuels, of which 8 were first-generation fuels.

The next sub-question was to determine the technological feasibility, cost/benefit, stakeholder acceptability, and timescale of adoption. The first had already been answered by only including ASTM approved fuels, and stakeholder acceptability is the use of second-generation fuels. The timescale of adoption is determined by acquiring cumulative production over the years for all fuels. Some fuels did not have any foreseeable production plans in the coming years; thus, they do not fulfil the timescale criterion. Only 8 fuels did have production plans, of which 3 were first-generation fuels. This leaves five eligible fuels for this research.

To determine the fuel's cost/benefit, it needed to be determined what future prices would be. Therefore, the experience curve theory is used to forecast future prices by looking at cumulative production increases. These future prices have been used to calculate the total costs of fuel per year needed to comply with the two scenarios that have been created.

Finally, market-based measures will influence the total cost outcome of this research. At first, the company saves money by partially not having to pay carbon offsets in the CORSIA and EU-ETS schemes due to the use of SAF. However, the carbon reduction per ton of fuel did often not comply with reaching the goals completely, especially in the net-zero scenario. Therefore, left-over carbon emissions that needed to be offset are being paid for in external carbon offsetting schemes. With these carbon credits, organisations invest in clean energy or planting trees.

The processes described above ultimately lead to the overview in Figure 7.9, which answers the main research question. The FT-SPK fuel made from Municipal Solid Waste is most cost-efficient from a business perspective, taking into account all regulations and goals. To reach the 50% reduction scenario, the company needs to invest 695 million USD (Net Present Value), resulting in an 89% minimum blending percentage of SAF, which means that 11% could still be fossil fuel while reaching the goal. For the net-zero scenario, an investment of 875 million USD is needed, and the blending percentage will be 120%, which is not possible. Therefore, 100% SAF is required in this scenario, while the left-over carbon emissions will be offset by acquiring carbon credits in other sectors.

With more than 300 million tonnes of $\mathrm{CO_2}$reduction potential per year for the FT-SPK fuel from Municipal Solid Waste, this is also the best fuel from a social perspective. Therefore, this fuel would be the best investment both in a social and from a business perspective.

8.2. Discussion

This research has brought valuable insights into the techno-economic implementation of SAF. By combining a traffic forecast and resulting $\mathrm{CO_2}$ emissions forecast for the period until 2050, a price development analysis using the experience curve, and the fill of the carbon reduction gap (to reach goals) with the implementation of SAF, a coherent and usable conclusion can be made.

Strengths

One of the strengths of this research is the differentiation of SAF alternatives and their characteristics; each alternative has its own price and carbon mitigation potential. Therefore, cheap SAF alternatives (such as HEFA-SPK made from palm oil) do not necessarily lead to a low investment cost, because the carbon mitigation power is low and, therefore, more SAF quantities are needed to realise a certain reduction. Although this insight was already publicly known, using this insight into this analysis could be seen as an asset.

One other important insight is the influence of price development (using the experience curve) on the results. Due to the maturity of the HEFA production process, price decrease is not expected, while other SAF alternatives have a decreasing price. Without the use of the experience curve analysis, HEFA-SPK from Used Cooking Oil would be the most attractive alternative in a business perspective (sensitivity analysis in section 6.4). However, the use of the experience curve ensured FT-SPK from Municipal Solid Waste to be more attractive.

Another strength is the adaptability of the research outcomes into aviation operations. The results give a clear view of the most attractive SAF alternatives, thus users of this research could focus on the implementation of only one or a limited number of fuels. Besides that, input parameters in the model can be changed easily, for instance when the growth prediction of air traffic demand seems to be different than what is estimated now.

Weaknesses

However, one major weakness of this research is that scientific knowledge on SAF minimum selling prices seems to be limited. Sources indicate a wide range of prices for SAF alternatives, which makes it difficult to give a reliable estimate or average that can be used as input in the model. Due to different methodologies of these sources, the prices could not be compared easily. The choice was made to give higher weights to the sources that were more recent, although there is no scientific foundation that supports this weighted average methodology. According to the sensitivity analysis in section 6.4, the minimum selling price is one of the most sensitive input parameters of the model, therefore the data reliability and quality is more important than for other input parameters.

Another weakness of the research is the poor reliability and usability of SAF production quantity data. The cumulative production of SAF alternatives is a major component in the determination of the SAF prices (with the experience curve method). The combination of the issues with minimum selling prices and cumulative production values ensures that the price prediction with the experience curve method is relatively unreliable.

A final weakness is the usage of Compound Annual Growth Rates (CAGR) to determine future air traffic demand. Although the data seem to be reliable, unforeseen changes in travel behaviour by consumers can influence the growth rate. This influences the CO_2 emission forecast and the resulting SAF quantities needed to fill the gap between the CO_2 forecast and the carbon reduction goals.

Generalisation

Although the research focused on the business perspective of TUI Aviation, this could be generalised toward the aviation sector in general. The two TUI-specific input parameters are the demand input of 2019 and the CAGRs which are related to the markets of TUI Aviation. However, changing these parameters does not give any other results in general, except the height of the Net Present Value of investment. For instance, changing the CAGR to another (i.e. negative) value or changing the demand input data, still results in FT-SPK from Municipal Solid Waste as being the most attractive fuel in a business perspective. Only the SAF offtake quantities and resulting costs are TUI-specific results, but changing the demand input and CAGR with data from another airline would result in quantities and costs related to that airline.

8.3. Recommendations

The recommendations for TUI Aviation will be discussed in subsection 8.3.1. These recommendations refer to the practicality, usability and improvement of the model and the resulting research. These are important for strategic decision-making within TUI Aviation (or the aviation industry in general). The recommendations for further research focus on the scientific limitations and possible improvements of this research and are discussed in subsection 8.3.2.

8.3.1. Recommendations for TUI Aviation

The general recommendation is to invest in the FT-SPK fuel made from Municipal Solid Waste. This fuel is most attractive in both a business and a social perspective. The high carbon reduction per tonne of fuel ensures a reliable fuel. The cumulative production increase will lead to a competitive price relative to fossil fuel. There is enough feedstock potential per year globally to reduce over 300 million tonnes of carbon emissions.

The user of the model, thus TUI Aviation, is encouraged to keep the computerised model up to date. Extra SAF alternatives could be added when they become available on the market (including the ASTM certification). One example is Power-to-Liquid fuels, that will have more carbon mitigation potential than any of the fuels mentioned in this research, as discussed in subsection 3.4.3.

Besides that, TUI Aviation could overwrite the weighted average Minimum Selling Price (MSP) of SAF alternatives in the model. The computerised model has a functionality in tab B1 where the user can fill in customised prices that overwrite the weighted average MSP. This can be valuable when the company receives offers or quotations from SAF suppliers, so they can work with real data instead of estimated data.

However, there is one caveat in this functionality. The model assumes that the MSP is based on the initial price in year $t = 2020$, which is assumed to be the start of fuel production. When future market prices are included in the model (for instance 2030 market prices), there already have been some years of production where learning and scaling effects (experience curve) already lowered the market price. The model will assume that the customised market price is the initial price at the start of the production. A solution would be to set the PR_i at 1, which will lead to an absence of learning and scaling effects in the model.

Another possibility for TUI Aviation is to add demand data for future years into the model. The years after will be forecasted by using the Compound Annual Growth Rates given by ICAO. By doing this, the model will be more reliable, especially because forecasting comes with an increasing uncertainty in a larger time-span.

One limitation of the model is that it doesn’t take a model shift in holiday travel into account. In subsection 3.3.2, it was discussed that modal shift is not considered because TUI Aviation destinations are practically impossible to reach by other modes, such as long-distance trains. Destinations include Southern Europe (including many islands) and countries beyond Europe. However, potential customers could also choose to change their holiday behaviour and search for destinations that are easily accessible by more sustainable modes of transportation.

One solution to comply with modal shift is to add the demand data for future years into the model, as discussed above. Another possibility is to change the Compound Annual Growth Rate to a negative percentage, leading to a decrease in demand over time. When a hypothetical CAGR of -2% for all markets is used, the FT-SPK from Municipal Solid Waste is still the most preferable fuel. The main consequence in the model is that less SAF offtake quantities are needed to reach the goals, which influences the total NPV or investment costs.

8.3.2. Recommendations for further research

There are numerous possibilities for improvements that would improve scientific knowledge on this subject. One of the significant drawbacks of this research was that information about alternative fuels' prices was very hard to find. Relying on academic publishing is the only way to accomplish that because producers won't communicate their prices publicly due to confidentiality agreements with clients and not to enrich competitors with pricing information. Any new data availability developments would strengthen this model and the outcomes, mainly because the price inputs are a very sensitive parameter in the model.

It was very difficult to determine the fuels' future cumulative production, and used sources were not at an academic level, but mostly news articles and producers' websites. Besides that, some producers may keep their production targets confidential. The growth in cumulative production affects the experience curve used, and thus future prices of fuels. Therefore, updating and completing the Producers overview would benefit the model significantly.

The future prices of alternative fuels have been determined using the experience curve theory, but other monetary values play a role. Future research could focus on the future prices of fossil fuel (now it is set at a fixed price for the entire forecasting period). Besides that, carbon mitigation schemes such as CORSIA and EU-ETS could become more expensive in the future. Including price fluctuations and/or trends would be beneficial to the model and the outcomes' reliability.

This model is not finished, but it will become better when it is improved over time. For example, only fuels are included at the moment that already passed technological readiness tests and certifications. However, R&D is not at a standstill, and carbon-free fuels could be the future. One of the proposed technologies is Power-to-Liquid, including the capture of carbon emissions from the air that are converted into zero-carbon fuels. Because certification will take another couple of years and little about characteristics and pricing has been known publicly yet, it is better to wait and include these fuels later.

As discussed in section 6.4, the Carbon Mitigation Start Level is sensitive in one direction (only an NPV increase). Both with a 50% increase and 50% decrease of the start level, the result is that the NPV increases, resulting in more costs. There is an opportunity to find this apparent local optimum with the lowest NPV costs.

Finally, in subsection 3.4.3 was discussed that SAF implementation would have no or little influence on radiative forcing caused by contrails. However, future research may object that statement, especially because there is still a large scientific uncertainty around the effects of contrails on global warming. When new information is available, it would be useful to include the effects of contrails into this model in further research.

To conclude, this research still has a lot of uncertainties, such as future SAF production quantities, SAF Minimum Selling Prices, and the scope of SAF alternatives used in this research. Therefore, it is recommended that this model and research will be updated when new information is available in the future. Although some future knowledge could mitigate the benefits and negatively influence the outcomes, other future developments could bring larger benefits of CO_2 reduction and better outcomes. However, since the problem of climate change is unprecedented, it is better to start with actions (with the support of these research outcomes) than to wait until new information and research would be available.

Bibliography

[1] Abu-Rayash, A. and Dincer, I. Analysis of mobility trends during the COVID-19 coronavirus pandemic: Exploring the impacts on global aviation and travel in selected cities. *Energy Research & Social Science*, 68(July):101693, 10 2020. ISSN 22146296. doi: 10.1016/j.erss.2020.101693.

[2] Air France-KLM. Universal Registration Document 2019. Technical report, Air France-KLM, 2020.

[3] Air Transport Action Group. Aviation Benefits Beyond Borders. Powering global economic growth, trade links, tourism and support for sustainable development through air transport, despite global crisis. Technical report, Air Transport Action Group, 2020.

[4] Air Transport Action Group. Waypoint 2050. Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency. Technical report, Air Transport Action Group, 2020.

[5] Alaska Airlines. Creating Lift Through Sustainability. 2019 Report. Technical report, Alaska Airlines, 2020.

[6] Ali, R. What Shape Would the Travel Industry Recovery Look Like?, 4 2020. URL `https://skift.com/2020/04/12/what-shape-would-the-travel-industry-recovery-look-like/`.

[7] ANA Group. Connecting the world. Annual Report 2019. Technical report, ANA Group, 2020.

[8] Archer, B. H. Forecasting demand. *International Journal of Tourism Management*, 1(1): 5–12, 3 1980. ISSN 01432516. doi: 10.1016/0143-2516(80)90016-X.

[9] Arora, S. and Gangopadhyay, S. Toward a theoretical model of voluntary overcompliance. *Journal of Economic Behavior & Organization*, 28(3):289–309, 12 1995. ISSN 01672681. doi: 10.1016/0167-2681(95)00037-2.

[10] Bagnoli, M. and Watts, S. G. Selling to Socially Responsible Consumers: Competition and The Private Provision of Public Goods. *Journal of Economics & Management Strategy*, 12(3):419–445, 9 2003. ISSN 1058-6407. doi: 10.1111/j.1430-9134.2003.00419.x.

[11] Bann, S. J., Malina, R., Staples, M. D., Suresh, P., Pearlson, M., Tyner, W. E., Hileman, J. I., and Barrett, S. The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresource Technology*, 227:179–187, 2017. ISSN 09608524. doi: 10.1016/j.biortech.2016.12.032.

[12] Baral, N. R., Kavvada, O., Mendez-Perez, D., Mukhopadhyay, A., Lee, T. S., Simmons, B. A., and Scown, C. D. Techno-economic analysis and life-cycle greenhouse gas mitigation cost of five routes to bio-jet fuel blendstocks. *Energy & Environmental Science*, 12(3):807–824, 2019. ISSN 1754-5692. doi: 10.1039/C8EE03266A.

[13] Becattini, V., Gabrielli, P., and Mazzotti, M. Role of Carbon Capture, Storage, and Utilization to Enable a Net-Zero-CO 2 -Emissions Aviation Sector. *Industrial & Engineering Chemistry Research*, 1 2021. ISSN 0888-5885. doi: 10.1021/acs.iecr.0c05392.

[14] Biofuels FlightPath. Swedish proposal for a sustainable aviation fuel mandate in Sweden, 3 2019. URL `https://www.biofuelsflightpath.eu/news/60-swedish-proposal-for-an-alternative-aviation-fuel-mandate-in-sweden`.

[15] Black, W. The Historical Problem of Sustainability in the Transport Sector. In *Sustainable transportation: problems and solutions*, chapter 1, pages 13–22. Guilford Publications, 2010. ISBN 978-1-60623-485-3.

[16] Buijtendijk, H. and Eijgelaar, E. Understanding research impact manifestations in the environmental policy domain. Sustainable tourism research and the case of dutch aviation. *Journal of Sustainable Tourism*, 0(0):1–18, 5 2020. ISSN 0966-9582. doi: 10.1080/09669582.2020.1760872.

[17] Burkhardt, U., Bock, L., and Bier, A. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science*, 1(1): 37, 12 2018. ISSN 23973722. doi: 10.1038/s41612-018-0046-4.

[18] Caiazzo, F., Agarwal, A., Speth, R. L., and Barrett, S. R. Impact of biofuels on contrail warming. *Environmental Research Letters*, 12(11):114013, 11 2017. ISSN 17489326. doi: 10.1088/1748-9326/aa893b.

[19] Capaz, R. S., Guida, E., Seabra, J. E. A., Osseweijer, P., and Posada, J. A. Mitigating carbon emissions through sustainable aviation fuels: costs and potential. *Biofuels, Bioproducts and Biorefining*, page bbb.2168, 11 2020. ISSN 1932-104X. doi: 10.1002/bbb.2168.

[20] Cathay Pacific Airways Limited. Sustainable Development Report 2019. Technical report, Cathay Pacific Airways Limited, 2020.

[21] Cervi, W. R., Lamparelli, R. A. C., Seabra, J. E. A., Junginger, M., Jong, S., and Hilst, F. Spatial modeling of techno□economic potential of biojet fuel production in Brazil. *GCB Bioenergy*, 12(2):136–157, 2 2020. ISSN 1757-1693. doi: 10.1111/gcbb.12659.

[22] Chao, H., Agusdinata, D. B., and DeLaurentis, D. A. The potential impacts of Emissions Trading Scheme and biofuel options to carbon emissions of U.S. airlines. *Energy Policy*, 134(January):110993, 2019. ISSN 03014215. doi: 10.1016/j.enpol.2019.110993.

[23] Chuck, C. J., McManus, M., Allen, M. J., and Singh, S. Feedstocks for Aviation Biofuels. In *Biofuels for Aviation*, pages 17–34. Elsevier, 2016. ISBN 9780128045688. doi: 10.1016/B978-0-12-804568-8.00002-0.

[24] de Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., and Junginger, M. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioproducts and Biorefining*, 9(6):778–800, 11 2015. ISSN 1932104X. doi: 10.1002/bbb.1613.

[25] De Jong, S., Antonissen, K., Hoefnagels, R., Lonza, L., Wang, M., Faaij, A., and Junginger, M. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnology for Biofuels*, 10(1):64, 12 2017. ISSN 17546834. doi: 10.1186/s13068-017-0739-7.

[26] Delta Air Lines. Positive Change Powered By Connection: Corporate Responsibility Report 2019. Technical report, Delta Air Lines, 2020.

[27] Dietrich, R.-U., Albrecht, F. G., and Estelmann, S. Synthetic jet fuel from renewable energy sources for sustainable aviation, 6 2017.

[28] Doganis, R. *Airline Business in the 21st Century*. Routledge, 6 2005. ISBN 9780203991916. doi: 10.4324/9780203991916.

[29] Dosio, A. and Fischer, E. M. Will Half a Degree Make a Difference? Robust Projections of Indices of Mean and Extreme Climate in Europe Under 1.5{${}^\circ$}C, 2{${}^\circ$}C, and 3{${}^\circ$}C Global Warming. *Geophysical Research Letters*, 45 (2):935–944, 1 2018. ISSN 0094-8276. doi: 10.1002/2017GL076222.

[30] Dreborg, K. H. Essence of backcasting. *Futures*, 28(9):813–828, 11 1996. ISSN 00163287. doi: 10.1016/S0016-3287(96)00044-4.

[31] Drünert, S., Neuling, U., Zitscher, T., and Kaltschmitt, M. Power-to-Liquid fuels for aviation – Processes, resources and supply potential under German conditions. *Applied Energy*, 277(June):115578, 11 2020. ISSN 03062619. doi: 10.1016/j.apenergy.2020.115578.

[32] Dutch Emissions Authority. Updated monitoring rules for EU-ETS and CORSIA. URL `https://www.emissionsauthority.nl/topics/general---ets-aviation-and-corsia/updated-monitoring-rules-for-eu-ets-and-corsia`.

[33] Dzambazovski, K. and Metodijeski, D. Study on the effects on the private sector - tourism and hospitality, affected by the health and economic crisis caused by the COVID-19 pandemic, with recommendations for dealing with the economic effects. Technical report, Epi Centar International, Skopje, 2020.

[34] EASA. European Aviation Environmental Report 2019. Technical Report 1, EASA, EEA, EUROCONTROL, 2019. URL `https://www.eurocontrol.int/publication/european-aviation-environmental-report-2019`.

[35] European Commission. Reducing emissions from aviation | Climate Action. URL `https://ec.europa.eu/clima/policies/transport/aviation_en`.

[36] FedEx. Multiplying Opportunities. 2020 Global Citizenship Report. Technical report, FedEx, 2020.

[37] Festel, G., Würmseher, M., and Rammer, C. Scaling and Learning Effects of Biofuels Conversion Technologies. *Energy Technology*, 2(7):612–617, 2014. ISSN 21944288. doi: 10.1002/ente.201400014.

[38] Gegg, P., Budd, L., and Ison, S. The market development of aviation biofuel: Drivers and constraints. *Journal of Air Transport Management*, 39:34–40, 7 2014. ISSN 09696997. doi: 10.1016/j.jairtraman.2014.03.003.

[39] Gössling, S. Risks, resilience, and pathways to sustainable aviation: A COVID-19 perspective. *Journal of Air Transport Management*, 89(August):101933, 10 2020. ISSN 09696997. doi: 10.1016/j.jairtraman.2020.101933.

[40] Grote, M., Williams, I., and Preston, J. Direct carbon dioxide emissions from civil aircraft. *Atmospheric Environment*, 95:214–224, 10 2014. ISSN 18732844. doi: 10.1016/j.atmosenv.2014.06.042.

[41] Haryanto, T. Editorial: Covid-19 Pandemic and International Tourism Demand. *Journal of Developing Economies*, 5(1):1, 2020. ISSN 2541-1012. doi: 10.20473/jde.v5i1.19767.

[42] Hileman, J. I. and Stratton, R. W. Alternative jet fuel feasibility. *Transport Policy*, 34:52–62, 7 2014. ISSN 0967070X. doi: 10.1016/j.tranpol.2014.02.018.

[43] HM Government. The Ten Point Plan for a Green Industrial Revolution. Technical report, HM Government, 2020.

[44] Hoekstra, W. B. and van Nieuwenhuizen Wijbenga, C. Kamerbrief Steunmaatregelen KLM, 2020. URL `https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/kamerstukken/2020/06/26/kamerbrief-steunmaatregelen-klm/kamerbrief-steunmaatregelen-klm.pdf`.

[45] Iacus, S. M., Natale, F., Santamaria, C., Spyratos, S., and Vespe, M. Estimating and projecting air passenger traffic during the COVID-19 coronavirus outbreak and its socio-economic impact. *Safety Science*, 129:104791, 9 2020. ISSN 09257535. doi: 10.1016/j.ssci.2020.104791.

[46] IATA. IATA Sustainable Aviation Fuel Roadmap. Technical report, IATA, 2015.

[47] IATA. Fact Sheet 2: SAF Technical Certification. Technical report, IATA, 2019.

[48] IATA. Fuel Fact Sheet. Technical report, IATA, 2020. URL `https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-fuel.pdf`.

[49] ICAO. What is CORSIA and how does it work?, . URL `https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx`.

[50] ICAO. Trends in Emissions that affect Climate Change, . URL `https://www.icao.int/environmental-protection/Pages/ClimateChange_Trends.aspx`.

[51] ICAO. Estimated Prices of Aviation Alternative Fuels. Technical report, ICAO, 2017. URL `https://www.icao.int/Meetings/CAAF2/Documents/CAAF.2.WP.008.1.en.Estimated%0Aprices%0Aof%0AAAF.FINAL.pdf`.

[52] ICAO. Sustainable Aviation Fuels Guide. Technical report, ICAO, Montreal, 2017. URL `www.icao.int/environmental-protection/Pages/ICAO_UNDP.aspx`.

[53] ICAO. ICAO Long-Term Traffic Forecasts Passenger and Cargo. Technical report, ICAO, 2018.

[54] ICAO. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels. Technical report, ICAO, Montreal, 2019.

[55] ICAO. CORSIA Sustainability Criteria for CORSIA Eligible Fuels. Technical Report June, ICAO, Montreal, 2019. URL `https://www.icao.int/environmental-protection/CORSIA/Documents/`

ICAOdocument05-SustainabilityCriteria.pdfhttps://www.icao.int/environmental-protection/CORSIA/Documents/ICAOdocument05-SustainabilityCriteria.pdf.

[56] ICAO. CORSIA Methodology for Calculating Actual Life Cycle Emissions Values. Technical report, ICAO, Montreal, 2019.

[57] ICAO. ICAO Environmental Report 2019: Destination Green. The Next Chapter. Technical report, ICAO, Montreal, 2019.

[58] ICAO. CORSIA Eligible Emissions Units. Technical Report August, ICAO, 2020. URL https://www.icao.int/environmental-protection/CORSIA/Documents/TAB/TAB2020/ICAO_Doc_CORSIA_Eligible_Emissions_Units_March_2020.pdfhttps://www.icao.int/environmental-protection/CORSIA/Documents/TAB/TAB2020/ICAO_Doc_CORSIA_Eligible_Emissions_Units_March_.

[59] IndexMundi. Jet fuel daily price, 2020. URL https://www.indexmundi.com/commodities/?commodity=jet-fuel.

[60] International Airlines Group. Leading Sustainable Aviation: Annual Report and Accounts 2019. Technical report, International Airlines Group, 2020.

[61] InterVISTAS Consulting and NACO. Coronavirus Briefing Note #1: Scenarios for Recovery. Technical report, InterVISTAS Consulting, 2020.

[62] Janić, M. Greening the Airport Airside Area II: Liquid Hydrogen as an Alternative Fuel. In *Green Energy and Technology*, volume 52, pages 133–163. Springer-Verlag London Limited, 2011. ISBN 9780857296573. doi: 10.1007/978-0-85729-658-0{_}6.

[63] Janić, M. An assessment of the potential of alternative fuels for “greening” commercial air transportation. *Journal of Air Transport Management*, 69:235–247, 6 2018. ISSN 09696997. doi: 10.1016/j.jairtraman.2017.09.002.

[64] Japan Airlines. Fly Into Tomorrow. JAL Report 2019. Technical report, Japan Airlines, 2019.

[65] Jet Blue. Environmental Social Governance 2018. Technical report, Jet Blue, 2019.

[66] Johannesson, P. and Perjons, E. Research Strategies and Methods. In *An Introduction to Design Science*, pages 39–73. Springer International Publishing, Cham, 2014. ISBN 9783319106328. doi: 10.1007/978-3-319-10632-8{_}3.

[67] Jolly, J. Airlines may not recover from Covid-19 crisis for five years, says Airbus, 4 2020. URL https://www.theguardian.com/business/2020/apr/29/airlines-may-not-recover-from-covid-19-crisis-for-five-years-says-airbus.

[68] KLM Royal Dutch Airlines. Annual Report 2019. Technical report, KLM Royal Dutch Airlines, 2020.

[69] Kousoulidou, M. and Lonza, L. Biofuels in aviation: Fuel demand and CO2 emissions evolution in Europe toward 2030. *Transportation Research Part D: Transport and Environment*, 46:166–181, 7 2016. ISSN 13619209. doi: 10.1016/j.trd.2016.03.018.

[70] Kung, C. H. and Sölvberg, A. Activity modeling and behavior modeling. In *Proc. of the IFIP WG 8.1 Working Conference on Information Systems Design Methodologies: Improving the Practice*, pages 145–171, Noordwijkerhout, Netherlands, 1986. North-Holland Publishing Co. ISBN 0-444-70014-5. URL `http://dl.acm.org/citation.cfm?id=20143.20149`.

[71] Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C., Lim, L. L., Owen, B., and Sausen, R. Aviation and global climate change in the 21st century. *Atmospheric Environment*, 43(22-23):3520–3537, 7 2009. ISSN 13522310. doi: 10.1016/j.atmosenv.2009.04.024.

[72] Leila, M., Whalen, J., and Bergthorson, J. Strategic spatial and temporal design of renewable diesel and biojet fuel supply chains: Case study of California, USA. *Energy*, 156(2018):181–195, 8 2018. ISSN 03605442. doi: 10.1016/j.energy.2018.04.196.

[73] Li, X., Mupondwa, E., and Tabil, L. Technoeconomic analysis of biojet fuel production from camelina at commercial scale: Case of Canadian Prairies. *Bioresource Technology*, 249(September 2017):196–205, 2 2018. ISSN 09608524. doi: 10.1016/j.biortech.2017.09.183.

[74] Luchtvaartnieuws. 1,3 miljard euro verlies verwacht voor Air France-KLM, 10 2020. URL `https://www.luchtvaartnieuws.nl/nieuws/categorie/2/airlines/13-miljard-euro-verlies-verwacht-voor-air-france-klm`.

[75] Luchtvaartnieuws. Coronacrisis en afschrijvingen drukken IAG in het rood, 7 2020. URL `https://www.luchtvaartnieuws.nl/nieuws/categorie/2/airlines/coronacrisis-en-afschrijvingen-drukken-iag-in-het-rood`.

[76] Luchtvaartnieuws. 'Lufthansa overweegt geheel afscheid te nemen van A380, A340 en 747-400', 8 2020. URL `https://www.luchtvaartnieuws.nl/nieuws/categorie/2/airlines/lufthansa-overweegt-geheel-afscheid-te-nemen-van-a380-a340-en-747-400`.

[77] Luchtvaartnieuws. TUI-directeur Arjan Kers rekent op volledig herstel in 2022, 8 2020. URL `https://www.luchtvaartnieuws.nl/nieuws/categorie/72/algemeen/tui-directeur-arjan-kers-rekent-op-volledig-herstel-in-2022`.

[78] Lufthansa Group. Balance: Sustainability Report 2019. Technical report, Lufthansa Group, 2020.

[79] Lyon, T. P. and Maxwell, J. W. Corporate Social Responsibility and the Environment: A Theoretical Perspective. *Review of Environmental Economics and Policy*, 2(2):240–260, 7 2008. ISSN 1750-6816. doi: 10.1093/reep/ren004.

[80] Martinez-Hernandez, E., Ramírez-Verduzco, L. F., Amezcua-Allieri, M. A., and Aburto, J. Process simulation and techno-economic analysis of bio-jet fuel and green diesel production — Minimum selling prices. *Chemical Engineering Research and Design*, 146:60–70, 6 2019. ISSN 02638762. doi: 10.1016/j.cherd.2019.03.042.

[81] Mawhood, R., Gazis, E., de Jong, S., Hoefnagels, R., and Slade, R. Production pathways for renewable jet fuel: a review of commercialization status and future prospects. *Biofuels, Bioproducts and Biorefining*, 10(4):462–484, 7 2016. ISSN 1932104X. doi: 10.1002/bbb.1644.

[82] Mazareanu, E. R. COVID-19 impact on flight frequency of global airlines, 11 2020. URL `https://www.statista.com/statistics/1104036/novel-coronavirus-weekly-flights-change-airlines-region/`.

[83] Mazraati, M. World aviation fuel demand outlook. *OPEC Energy Review*, 34(1):42–72, 3 2010. ISSN 17530229. doi: 10.1111/j.1753-0237.2010.00174.x.

[84] Ministerie van IenW. Minister Van Nieuwenhuizen imposes use of cleaner fuel in aviation sector, 3 2020. URL `https://www.government.nl/latest/news/2020/03/04/minister-van-nieuwenhuizen-imposes-use-of-cleaner-fuel-in-aviation-sector`.

[85] Moore, R. H., Thornhill, K. L., Weinzierl, B., Sauer, D., D'Ascoli, E., Kim, J., Lichtenstern, M., Scheibe, M., Beaton, B., Beyersdorf, A. J., Barrick, J., Bulzan, D., Corr, C. A., Crosbie, E., Jurkat, T., Martin, R., Riddick, D., Shook, M., Slover, G., Voigt, C., White, R., Winstead, E., Yasky, R., Ziemba, L. D., Brown, A., Schlager, H., and Anderson, B. E. Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. *Nature*, 543(7645):411–415, 3 2017. ISSN 14764687. doi: 10.1038/nature21420.

[86] Morris, J., Rowbotham, A., Angus, A., Mann, M., and Poll, I. A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector. OMEGA Project 14 – Final Report. Technical Report January, Cranfield University, Bedford, 2009.

[87] Mustapha, W. F., Bolkesjø, T. F., Martinsen, T., and Trømborg, E. Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning. *Energy Conversion and Management*, 149: 368–380, 2017. ISSN 01968904. doi: 10.1016/j.enconman.2017.07.004.

[88] Nigam, P. S. and Singh, A. Production of liquid biofuels from renewable resources. *Progress in Energy and Combustion Science*, 37(1):52–68, 2 2011. ISSN 03601285. doi: 10.1016/j.pecs.2010.01.003.

[89] Nilson, K. and Tuvlind, A. *Carbon Offsetting and Sustainable Aviation: A study of contemporary and future sustainable aviation via carbon offsetting*. PhD thesis, KTH Royal Institute of Technology, 2020.

[90] Noh, H. M., Benito, A., and Alonso, G. Study of the current incentive rules and mechanisms to promote biofuel use in the EU and their possible application to the civil aviation sector. *Transportation Research Part D: Transport and Environment*, 46(2016):298–316, 7 2016. ISSN 13619209. doi: 10.1016/j.trd.2016.04.007.

[91] NU.nl. TUI-baas optimistisch over 2021 en verwacht een 'grotendeels normale zomer', 1 2021. URL `https://www.nu.nl/economie/6099847/tui-baas-optimistisch-over-2021-en-verwacht-een-grotendeels-normale-zomer.html`.

[92] Oberkampf, W. L., Trucano, T. G., and Hirsch, C. Verification, validation, and predictive capability in computational engineering and physics. *Applied Mechanics Reviews*, 57 (5):345–384, 9 2004. ISSN 0003-6900. doi: 10.1115/1.1767847.

[93] oneworld Alliance. oneworld member airlines commit to net zero carbon emissions by 2050, 2020. URL `https://www.oneworld.com/news/2020-09-11-oneworld-member-airlines-commit-to-net-zero-carbon-emissions-by-2`

[94] Patruno, A., Amicarelli, V., and Lagioia, G. Aviation Fuel Evolution: a Review. *13th International Conference of ASECU*, 2016.

[95] Pavlenko, A. N., Searle, S., and Christensen, A. The cost of supporting alternative jet fuels in the European Union. Technical Report March, International Council on Clean Transportation, 2019.

[96] Peeters, P., Higham, J. E. S., Kutzner, D., Cohen, S. A., and Gössling, S. Are technology myths stalling aviation climate policy? *Transportation Research Part D: Transport and Environment*, 44:30–42, 5 2016. ISSN 13619209. doi: 10.1016/j.trd.2016.02.004.

[97] Primeaux, P. and Stieber, J. Profit maximization: The ethical mandate of business. *Journal of Business Ethics*, 13(4):287–294, 4 1994. ISSN 0167-4544. doi: 10.1007/BF00871675. URL `http://link.springer.com/10.1007/BF00871675`.

[98] Qantas. Our Commitment to Environmental Sustainability. Technical report, Qantas, 2015.

[99] Remkes, J. W., Dijkgraaf, E., Freriks, A., Gerbrandy, G. J., Maij, W. H., Nijhof, A. G., Post, E., Rabbinge, R., Scholten, M., and Vet, L. E. M. Niet alles kan : Eerste advies van het Adviescollege Stikstofproblematiek: aanbevelingen voor korte termijn 25 september 2019. Technical report, Adviescollege Stikstofproblematiek, 2019. URL `https://edepot.wur.nl/501323`.

[100] SAS. SAS Annual and Sustainability Report Fiscal Year 2019. Technical report, SAS, 2020.

[101] Schäfer, A. W. The Prospects for Biofuels in Aviation. In *Biofuels for Aviation*, pages 3–16. Elsevier, 2016. ISBN 9780128045688. doi: 10.1016/B978-0-12-804568-8.00001-9.

[102] Schlesinger, S. Terminology for Model Credibility. *Simulation*, 32(3):103–104, 1979. URL `http://ci.nii.ac.jp/naid/10029829502/en/`.

[103] Sgouridis, S., Bonnefoy, P. A., and Hansman, R. J. Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation. *Transportation Research Part A: Policy and Practice*, 45(10):1077–1091, 12 2011. ISSN 09658564. doi: 10.1016/j.tra.2010.03.019.

[104] Simple Flying. Emirates Could Take Until 2024 To Return To Normal, 6 2020. URL `https://simpleflying.com/emirates-2024-normality/`.

[105] Simple Flying. Jet2 Expects Demand To Largely Recover In One Year, 9 2020. URL `https://simpleflying.com/jet2-demand-recovery/`.

[106] Simple Flying. Ryanair's Traffic Has Already Recovered By Half, 9 2020. URL `https://simpleflying.com/ryanairs-traffic-has-already-recovered-by-half/`.

[107] Simple Flying. Wizz Air Sees A Full Recovery Taking Just 12 Months, 6 2020. URL `https://simpleflying.com/wizz-air-sees-a-full-recovery-taking-just-12-months/`.

[108] Singapore Airlines. Sustainability Report FY2019/20. Technical report, Singapore Airlines, 2020.

[109] Slaper, T. F. and Hall, T. J. The Triple Bottom Line: What Is It and How Does It Work? *Indiana Business Review*, 86(Spring 2011), 2011.

[110] Smit, S., Hirt, M., Buehler, K., Lund, S., Greenberg, E., Govindarajan, A., Practice, C. F., Borgstein, J., Alan, F., Vivien, S., Sven, S., Kissler, S. M., Tedijanto, C., Goldstein, E., Grad, Y. H., Lipsitch, M., Mieszala, J.-c., Sneader, K., Singhal, S., Mendy, A., Stewart, M. L., and VanAkin, K. Safeguarding our lives and our livelihoods: the imperative of our time. *McKinsey & Company*, 372(April):11, 2020. ISSN 0038092X.

[111] Soubly, K., Wolff, C., Uppink, L., Riefer, D., Kienzler, C., Dichter, A., Pinner, D., Riede, R., Melgin, T., Mucha, A., Vernet, C., and Göthel, H. Clean Skies for Tomorrow. Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. Technical Report November, World Economic Forum, McKinsey & Company, 2020.

[112] Southwest Airlines. One Report 2019. Technical report, Southwest Airlines, 2020.

[113] Squadrin, G. and Schmit, F. Europe makes legislative push for aviation transition, 9 2020. URL `https://www.argusmedia.com/en/news/2145902-europe-makes-legislative-push-for-aviation-transition`.

[114] Staples, M. D., Malina, R., Olcay, H., Pearlson, M. N., Hileman, J. I., Boies, A., and Barrett, S. R. H. Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy Environ. Sci.*, 7(5):1545–1554, 2014. ISSN 1754-5692. doi: 10.1039/C3EE43655A.

[115] Staples, M. D., Malina, R., Suresh, P., Hileman, J. I., and Barrett, S. Aviation CO2 emissions reductions from the use of alternative jet fuels. *Energy Policy*, 114:342–354, 2018. ISSN 03014215. doi: 10.1016/j.enpol.2017.12.007.

[116] Swana, J., Yang, Y., Behnam, M., and Thompson, R. An analysis of net energy production and feedstock availability for biobutanol and bioethanol. *Bioresource Technology*, 102(2):2112–2117, 1 2011. ISSN 09608524. doi: 10.1016/j.biortech.2010.08.051.

[117] Topham, G. and Harvey, F. Airlines lobby to rewrite carbon deal in light of coronavirus, 2020. URL `https://www.theguardian.com/business/2020/apr/08/airlines-lobby-to-rewrite-carbon-deal-due-to-coronavirus`.

[118] TUI Group. Step lightly, . URL `https://www.tuigroup.com/en-en/responsibility/strategy/step-lightly`.

[119] TUI Group. Sustainable Development Goals, . URL `https://www.tuigroup.com/en-en/responsibility/strategy/SDGs`.

[120] TUI Group. We will drive environmental improvements across our aviation operations, . URL `https://www.tuigroup.com/en-en/responsibility/sus_business/airline`.

[121] Turgut, E. T. and Rosen, M. A. Emission assessment of aviation. In *Technology Engineering and Management in Aviation: Advancements and Discoveries*, pages 20–72. IGI Global, 2011. ISBN 9781609608873. doi: 10.4018/978-1-60960-887-3.ch002.

[122] United Airlines. CRR 2018 Environment Carbon emissions. URL `http://crreport.united.com/fact-sheets/environment`.

[123] United Nations Sustainable Development. Take Action for the Sustainable Development Goals, 2020. URL https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

[124] Unnikrishnan, M. Don't Count on Airlines to Recover for 3 Years, 4 2020. URL https://skift.com/2020/04/22/dont-count-on-airlines-to-fully-recover-for-3-years-delta-ceo/.

[125] van den Wall Bake, J. D., Junginger, M., Faaij, A., Poot, T., and Walter, A. Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and Bioenergy*, 33(4):644–658, 2009. ISSN 09619534. doi: 10.1016/j.biombioe.2008.10.006.

[126] van Velzen, A., de Bruyn, S., and Bachaus, A. Costs of EU ETS and CORSIA for European aviation. Technical report, CE Delft, 11 2019.

[127] Vela-García, N., Bolonio, D., Mosquera, A. M., Ortega, M. F., García-Martínez, M.-J., and Canoira, L. Techno-economic and life cycle assessment of triisobutane production and its suitability as biojet fuel. *Applied Energy*, 268(March):114897, 6 2020. ISSN 03062619. doi: 10.1016/j.apenergy.2020.114897.

[128] Virgin Atlantic. Virgin Atlantic Sustainability Report 2019. Technical report, Virgin Atlantic, 2019.

[129] Virgin Australia. FY19 Sustainable Development Report. Technical report, Virgin Australia, 2019.

[130] Wang, W.-C., Tao, L., Markham, J., Zhang, Y., Tan, E., Batan, L., Biddy, M., Wang, W.-C., Tao, L., Zhang, Y., Tan, E., Warner, E., and Biddy, M. Review of Biojet Fuel Conversion Technologies. Technical Report July, National Renewable Energy Laboratory, 2016. URL https://www.nrel.gov/docs/fy16osti/66291.pdf.

[131] Warshay, B., Pan, J., and Sgouridis, S. Aviation industry's quest for a sustainable fuel: Considerations of scale and modal opportunity carbon benefit. *Biofuels*, 2(1):33–58, 1 2011. ISSN 17597269. doi: 10.4155/bfs.10.70.

[132] Watts, J. Is the Covid-19 crisis the catalyst for greening the world's airlines?, 2020. URL https://www.theguardian.com/world/2020/may/17/is-covid-19-crisis-the-catalyst-for-the-greening-of-worlds-airlines.

[133] Wei, H., Liu, W., Chen, X., Yang, Q., Li, J., and Chen, H. Renewable bio-jet fuel production for aviation: A review. *Fuel*, 254:115599, 10 2019. ISSN 00162361. doi: 10.1016/j.fuel.2019.06.007.

[134] Weiss, M., Junginger, M., Patel, M. K., and Blok, K. A review of experience curve analyses for energy demand technologies. *Technological Forecasting and Social Change*, 77(3):411–428, 2010. ISSN 00401625. doi: 10.1016/j.techfore.2009.10.009.

[135] Wright, T. P. Factors Affecting the Cost of Airplanes. *Journal of the Aeronautical Sciences*, 3(4):122–128, 2 1936. ISSN 1936-9956. doi: 10.2514/8.155.

[136] Yilmaz, I., Ilbaş, M., Taştan, M., and Tarhan, C. Investigation of hydrogen usage in aviation industry. *Energy Conversion and Management*, 63:63–69, 11 2012. ISSN 01968904. doi: 10.1016/j.enconman.2011.12.032.

[137] Zaporozhets, O., Isaienko, V., and Synylo, K. Trends on current and forecasted aircraft hybrid electric architectures and their impact on environment. *Energy*, 211:118814, 11 2020. ISSN 03605442. doi: 10.1016/j.energy.2020.118814.

A

Research Paper

The paper can be found on the next pages.

Techno-economic Analysis of Sustainable Aviation Fuels by Using Traffic Forecasts and Fuel Price Projections: a Case Study at TUI Aviation

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Abstract—**This research focused on the techno-economic implementation of Sustainable Aviation Fuels (SAF). Carbon reduction in commercial aviation could be done via four key levers; technological efficiency improvement (aircraft or engine replacement), operational efficiency improvement (air traffic management or airline operations), the implementation of Sustainable Aviation Fuels, and carbon offsetting by using economic measures. This research was done by doing a case study at TUI Aviation, thus using their demand data. After developing a traffic forecast and resulting CO_2 forecast, the four levers were used to limit carbon emissions toward a net-zero emission scenario in 2050. The 22 ASTM certified SAF alternatives were tested against carbon mitigation power and costs, the latter being determined by using the experience curve theory of decreased prices with increased cumulative production. This results in the FT-SPK fuel made from Municipal Solid Waste as being the most attractive SAF alternative with a Net Present Value of 875 million USD. However, it is recommended to include extra fuel alternatives in this research in the future. For example, Power-to-Liquid fuels will have great potential, but are not certified yet.**

Index Terms—**Aviation, aircraft emissions, environmental economics, traffic forecasting, cost-benefit analysis, experience curve, sustainable mobility**

I. INTRODUCTION

The total oil demand share of aviation in the transportation sector is 11.2% [1], which ensures aviation being the second major consumer of oil [2]. Commercial aviation is responsible for 2.6% of global CO_2 emissions, while the sector is growing at 5% per annum [3]. The International Civil Aviation Organization (ICAO) expects that annual CO_2 emissions would grow by more than 300% by 2050 without additional measures [4]. As this has a significant impact on climate change, it is recommended to make commercial aviation greener.

A solution is to introduce Sustainable Aviation Fuel (SAF), which is made from non-fossil feedstock. The use of SAF would reduce greenhouse effects, reduce fossil oil dependency, improve air quality and create new job opportunities [5]. In a scenario where 100% of the fuel consumption would be SAF in 2050, there would only be a 63% reduction in emissions [4], due to emissions during production. Scaling up SAF use would require large capital investments in production infrastructure, and substantial policy support is necessary.

Staples et al. [3] note that a full replacement of fossil-based jet fuel with sustainable aviation fuel in 2050 may result in an absolute increase in greenhouse gas emissions in the aviation industry compared to 2005. In this paper, the projected fuel demand increase in 2050 is estimated to be higher than the projected emissions reduction by introducing SAF, which causes this absolute increase in emissions. This means that further emissions reduction could be needed to reach goals, for example with the use of CO_2 offsets from other sectors.

Previous research focused on the technological feasibility of SAF, or the urgency to implement SAF, but little research has been done into the economic feasibility of SAF. The only techno-economic analyses that can be found are papers that focus on either one or a limited number of SAF alternatives [6] [7] [8]. Still, there is a research gap that compares all relevant SAF alternatives into one research.

Besides that, no research has been found that states the increase of SAF production and how it would influence SAF alternatives' future prices. Combining these factors into one research would give a clear and complete view of SAF alternatives' attractiveness for the aviation industry.

II. RESEARCH OBJECTIVE

This research aims to determine which Sustainable Aviation Fuels are most attractive from a business perspective. This is done by delivering the Net Present Value of the investment needed for implementing each existing SAF alternative. The research starts with a stakeholder analysis to determine the main policies and regulations regarding carbon mitigation in commercial aviation.

It is required to know what SAF quantities need to be implemented. To be able to find those quantities, a traffic forecast is done. This determines future air traffic in the period 2020-2050, taking into account the COVID-19 crisis. This traffic forecast is converted into CO_2 emissions, taking into account external factors that would reduce carbon emissions. The gap between this CO_2 emission forecast and the carbon goals needs to be filled by introducing SAF. Each of the SAF alternatives has its characteristics, like the production pathway (synthesis technology), energy feedstock, emissions reduction and future cost projection. These characteristics are taken into account in the Net Present Values of the required investment costs for implementing the SAF alternatives, leading to differences in attractiveness. The ultimate objective is to deliver a Net Present Value of the investment needed for each of the SAF alternatives separately (Total Cost of Ownership).

This research is done by doing a case study at TUI Aviation. The TUI Group is the world's largest tourism agency and operates 5 airlines in the United Kingdom, Germany, Belgium, the Netherlands and Sweden. The outcome of this research will be a leading source in the development of a SAF implementation strategy within the TUI Group.

III. RESEARCH METHODS

A. *Framework*

In Figure 1, the research framework can be found. The first step is the literature review of specific concepts and principles in the Theory chapter. This is followed by the creation of a conceptual model, which translates the concepts and principles into model components. In the computerised model, the data analysis methods have their place. The output of these analyses will be used in the final analysis, where the SAF alternatives will be compared in a Cost-Benefit Analysis. The finished computerised model will be verified and validated to ensure the model works correctly, and the output is reliable. After that, The Cost-Benefit Analysis output will be used in a sensitivity analysis by testing the input variables' sensitivity. The output of the computerised model is the Net Present Value, resulting from the Cost-Benefit Analysis.

B. *Literature review and data collection*

Data collection is specified in three main categories; traffic forecast data, SAF characteristics, and stakeholder goals and regulations.

Operational data of 2019 is retrieved from the TUI Aviation database and used to measure air traffic in 2019. General air traffic growth data is extracted from literature. Recovery analysis regarding COVID-19 is done by searching for industry expert statements because academic research was not available at the start of this research. Data on SAF alternatives and their characteristics (carbon mitigation, technology readiness, availability, cost) is retrieved via a literature review. Stakeholder data is retrieved from a literature review to find policies, regulations and goals regarding carbon mitigation in aviation.

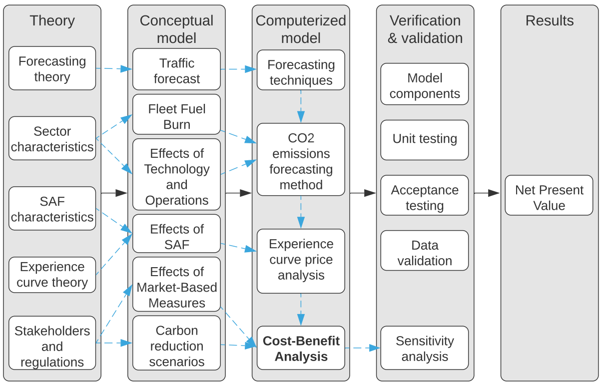


Fig. 1: Research framework

C. *Data analysis*

After data has been retrieved, an analysis to predict the future CO_2 emissions trend is established. Then, the corresponding response to this trend for the introduction of SAF is calculated.

1) CO2 emissions forecasting method: Data analysis is mainly based on the CO_2 emissions forecasting method from the Air Transport Action Group [9]. The ATAG method is developed to measure the effects of (1) traffic forecasts, (2) fleet fuel burn forecasts, (3) effects of technology and operations, (4) effects of alternative fuels, and (5) the effects of emission reductions from other sectors (Market-Based Measures). These five steps ultimately lead to the goal on the right side of Figure 2. Backcasting is possible by changing one or multiple steps above to see the effects on the CO_2 forecast and comply with the goal.

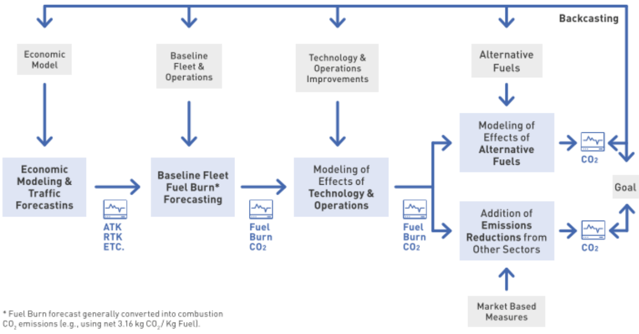


Fig. 2: Method for forecasting CO_2 emissions. Adapted from ATAG [9]

2) Air traffic forecasting techniques: The forecasting analysis will start with a qualitative technique. After the literature review, an estimation is being made of the recovery process after COVID-19. By the unique character of this crisis, it is hard to estimate demand by a quantitative method. Expert opinions are arguably more valuable. At the point of recovery (the moment of which the traffic forecast is equal to the period before the COVID-19 crisis), quantitative forecasting is more thrust-worthy. A time-series technique with trend will be used that takes TUI-specific trend values into account.

3) Experience curve price analysis: It is important what the future production costs (or prices) are for the highest-ranked SAF alternatives. The trading market for SAF is opaque [10]. There is no referenced market price for SAF like other products, such as crude oil or Fossil Aviation Fuel. An "experience curve" advances at different speeds in an undeveloped market of both supply and demands. Weiss et al. [11] used a methodology, including an experience curve approach suitable for this research.

4) Cost-Benefit Analysis: The most attractive alternative in a business perspective is the fuel that has the best Net Present Value for a 30 year period in a Cost-Benefit Analysis, taking into account the CO_2 reduction road-map that will be made and the SAF offtake that is needed to reach the goals of the CO_2 reduction road-map. The analysis will be based on cost-minimisation.

IV. THEORY AND DATA COLLECTION

This section will discuss the theoretical foundation that is needed to execute this analysis. It also includes initial data collection found in literature that is necessary for further steps.

A. Stakeholders and regulations

1) International organizations: CORSIA is a global scheme developed by ICAO to ensure carbon-neutral growth from 2021 onward [12]. Any growth in carbon emissions from international flights above the baseline comes with a cost; airlines have to pay to offset these. The EU-ETS is a way for the EU to reduce greenhouse gas emissions [13]. It is the world's first major carbon market (since 2005) and remains the largest one. CORSIA costs around 15 USD/ton (only emissions above 2019 baseline), while EU-ETS costs 50 USD/ton [14].

2) National governments: Some national governments are setting up mandates to blend SAF into conventional jet fuel. The Nordic countries are at the forefront of SAF mandates, with Finland and Sweden striving for a 30% SAF blending mandate in 2030 [15]. Sweden wants to increase that mandate to 100% in 2045 [16]. France starts with a 1% quota in 2022, which will gradually increase to 5% in 2030 and 50% in 2050 [15], while Germany published a draft quota to start with 0.5% in 2025, increasing to 2% in 2030. The Netherlands imposes the use of 14% SAF in 2030 [17], which increases to 100% in 2050. Norway started with a 0.5% fuel mandate in 2020 and is considering a 30% blend in 2030 [18], and in 2025 Spain will have a 2% SAF supply objective. The United Kingdom is investigating possibilities to introduce a mandate in 2025 [19]. These mandates, both decisions and considerations, are included in Table III in the Appendix.

3) Voluntary offsetting programs: Besides international and governmental goals and regulations, there are also international organisations that offer voluntary offsetting [20]. ICAO stated some voluntary carbon offsetting organisations that have the right certifications and invest in, e.g. clean energy and planting trees [21], which cost approximately 10 USD per tonne of CO_2. The main disadvantage of these voluntary carbon offsets is that they don't mitigate CO_2 immediately. It takes a long time for trees to grow and sequester the planned amount of CO_2 [20]. SAF is a better solution because it prevents the extraction of extra carbon by pumping crude oil.

4) Other airlines: Since the Paris Agreement and the set up of the UN Sustainable Development Goals, most airlines have been formulating their carbon reduction goals. The International Air Transport Association (IATA) set up an industry-wide goal to achieve a 50% reduction of carbon emissions in 2050 compared to 2005.

The environmental reports of the respective airlines are used to retrieve the information. Some airlines did not state any specific carbon reduction goals, and others stick to the IATA guidelines. The Oneworld alliance (with British Airways, American Airlines, Qatar Airways, among others) even formulated the goal to have net-zero emissions in 2050 [22].

B. Forecasting theory

The time-series method involves analysing linear and exponential trends, cyclical (seasonality) changes, and combined linear/exponential and cyclical changes. Two other main techniques are the moving average technique, and the exponential smoothing technique [23]. However, it is impossible to use these techniques to calculate forecasts until 2050 due to a lack of observations.

To tackle the problem described above, it is better to use trend extrapolation. Future growth rates are needed that can be applied from a baseline year. For example, Lee et al. [24] note that annual passenger traffic growth was 5.3% a year between 2000 and 2007. Janic [25] gives a growth rate of 5.4%. However, these growth rates have a global perspective, which would not apply to a TUI Aviation case study.

ICAO [26] uses RPK in their calculations and notes that the Compound Annual Growth Rate (CAGR) for 2015-2035 is 4.3% per year, while it is 4.1% per year for 2015-2045. Most of this growth can be found in Asia, while the market in Europe is more stabilised. They mention that for Intra Europe flights, only 2.6% CAGR is expected.

Before working with the growth rates discussed above, it is needed to determine the baseline year. COVID-19 has impacted the aviation industry, thus using the CAGR with a baseline year before the COVID crisis would give false results. This baseline (2020 or later) will have the same demand as 2019. Therefore, demand-data from 2019 can be used in the estimated baseline year, from which the trend extrapolation with growth rates can start.

Ali [27] expects the air travel industry to need a five-year recovery cycle to come to pre-COVID levels. Plane manufacturer Airbus has warned that the aviation sector could take three to five years to recover [28]. Delta Air Lines CEO Ed Bastian expects air travel not to rebound to pre-pandemic levels for another three years [29]. Deutsche Bank expects Air France-KLM to be recovered in 2024 [30], with a W-shaped recovery path. Lufthansa takes 2024 into account, too [31], just as Emirates [32]. International Airlines Group (IAG), with British Airways and Iberia, states that it will take at least until 2023 before air transport demand is fully recovered [33].

TUI Netherlands managing director Arjan Kers states that the demand for air tourism (package holidays) would be recovered to 80% in 2021, with a full recovery in 2022 [34]. More recently, TUI Group CEO Fritz Joussen stated that around 80% of the flights would be operated during the 2021 summer season, with a full recovery expected in 2022 due to the roll-out of the COVID vaccine [35]. The main reason for this is that TUI is not dependent on the recovery of business traffic, whereas the legacy carriers named above do. Business travellers (temporarily) replace travels with online meetings, while a digital solution can not replace a holiday experience.

C. Sector characteristics

1) Carbon mitigation: As shown in Figure 3, the expected aviation emissions would triple toward 2050 without additional measures. Some of the carbon reduction could be realised by technology, operations and infrastructure measures (fleet replacement, use of larger aircraft, increased density seating inside aircraft, improvements in Air Traffic Control and navigation procedures [36]). However, this won't be enough to reach the goals set by the aviation industry. Economic measures (like carbon mitigation schemes; the red plane in Figure 3) are only meant as a short-term solution. Therefore, Sustainable Aviation Fuels are needed to reach the goals in the industry.

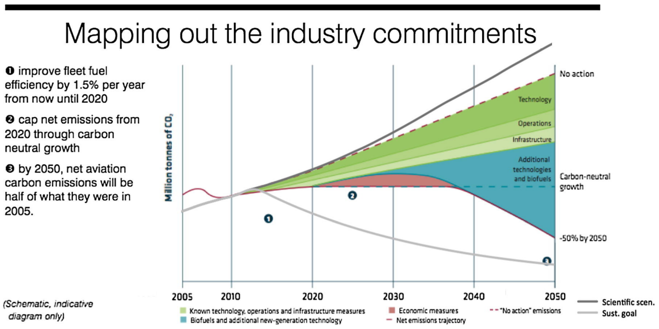


Fig. 3: Long term targets for international aviation CO_2 emissions. Adapted from Peeters et al. [37]

The technological efficiency is related to a set of measures related to aircraft performance [38], and are the main responsibility of the aircraft manufacturer. The improvement per year is estimated to be 1.9% [38], 1.29% to 1.37% [39], 1.16% [40], or 1% [41].

Some examples of operational efficiency improvements are optimized flight operations, such as fuel optimized climb/flight/descent paths, reduced cruise speeds, optimum altitudes, and reduced delays by Air Traffic Control [38]. This improvement is estimated to be 12% in total until 2050 [38], others indicate 6% to 9% [39], and 6% [9].

Another key lever is economic measures, such as carbon pricing. A Market-Based Measure (MBM) can be used as a mechanism to increase the effective price of fuel. This ensures a reduction in fuel demand through the price-demand elasticity relationship [38].

The last lever is using sustainable aviation fuels to lower the life cycle emissions of the used fuel. Because the carbon mitigation measures above are not sufficient to reach goals, as shown in Figure 3, SAF is needed to accomplish that.

2) Fuel economics: Aviation fuel prices fluctuate, just as the crude oil prices. Airlines had a 188 billion USD fuel bill in 2019, accounting for 23.7% of the operating expenses of airlines [42].

Normally, the fuel of an aircraft is uplifted (fuelled) in litres (l) or US Gallons (USG). However, the calculation to CO_2 is calculated from kilograms (kg), with 1 kg of Fossil Fuel being equal to 3.16 kg of CO_2. To calculate the uplift in kg, a standard value density of 0.8 kg/l is used [43].

D. SAF characteristics

SAF is a term that is normally referred to non-fossil derived aviation fuel [9]. It needs to be **Sustainable**; thus, it must be repeatedly and continually resourced in a manner that is consistent with economic, social and environmental aims. **Alternative** feedstock to crude oil must be used, which includes any materials or substances that can be used as fuels, other than fossil sources. The outcome is **fuel** that must meet the technical and certification requirements for use in existing commercial aircraft.

1) SAF, Hydrogen or Electric propulsion: Aircraft configurations with electric propulsion are being developed and available after 2030 [39]. However, batteries are heavy, and liquid hydrogen needs a large volume of well-insulated fuel tanks, making it inefficient for long distances [44]. Therefore, this research will focus on SAF.

2) Feedstocks: There are numerous feedstocks possible to develop SAF. Feedstock production is the first step in the production of SAF. Feedstocks are categorised by the usable materials. Sugar or starch-bearing feedstocks are fermentable plants, which can be transformed into alcohol, from which SAF can be obtained [45]. Oil-bearing feedstocks are a widely used feedstock and can be transformed into SAF by hydrogen addition [45]. Lignocellulosic feedstocks, such as wood and wood residues, can be obtained from rotation forestry, or as residues from wood processing industries.

A feedstock can be either be a first or second-generation feedstock [46]. A first-generation feedstock can be used for producing both fuel and food, therefore conflicting world food supply. Besides that, there is less promise in reducing CO_2 emissions.

3) Production pathways: The standard that handles the certification of SAF is ASTM D7566 [47]. If a production pathway is accepted by this certification, it is evaluated that this technology can produce SAF under specific circumstances and characteristics. The certification of the fuel does not necessarily mean that the fuel is sustainable.

Three main production processes are certified at the moment [47]. The first is Hydroprocessed Esters and Fatty Acids (HEFA), which can use oil-bearing feedstock such as Used Cooking Oil (UCO) or Non-Food Plant Oils (such as Carinata seeds). The second is Fischer-Tropsch (FT), which uses either Municipal Solid Waste (MSW), Agricultural or Forestry Residues. The latter is Alcohol-To-Jet (ATJ), which often uses sugar-bearing feedstock, but it is also possible to use other resources like MSW. A new and extra process is Hydroprocessed Fermented Sugars (HFS or DSHC).

4) Life Cycle Assessment: The production, conversion, and transportation of these novel fuels cause emissions. Therefore, Life Cycle Assessment (LCA) is a tool to determine the environmental impact of fuels. LCA addresses the environmental aspects, and their potential impacts throughout the life cycle of a product [45].

Greenhouse gas emissions associated with Land Use Change (LUC) are among the main issues regarding LCA [45]. The production of biofuel feedstock, directly and indirectly, leads to changes in agricultural land use, this is called dLUC and iLUC. The direct effect is that land is needed to produce the feedstock, which is either taken from agricultural land previously used for food production, or natural vegetation such as forests. iLUC is the effect of food production needing to move to another place (mostly out of scope), for which new agricultural land is necessary.

5) Minimum Selling Price: The Minimum Selling Price (MSP) for fuel is the price that producers of a fuel can afford to ask customers to fulfil the production's capital and operational expenditures.

The different sources could not be compared easily due to other research methods and years in which the research was executed. Therefore, there has been chosen to apply a weighted average to determine the MSP that will be used in the analysis, assuming the most recent research will show the most accurate results. The oldest source [48] gets a weight of 1, while an extra year will receive an additional value 1, which ensures that the newest sources both receive a weight of 7 [49] [50]. The results can be found in Table II in the Appendix. These weighted average MSPs will be used as input in the model.

Two criteria have been used to assemble a preliminary list of fuels that are included in this research; fuels need to be ASTM certified, and they need to be eligible to CORSIA requirements [51].

E. Experience curve theory

Festel et al. [52] use a scaling and learning effects methodology to analyse biofuels conversion technologies. The scaling effects refer to the production scale size, while technological advantages cause the learning effects. The experience curve formulated by Weiss et al. [11] expresses production costs (or prices) of technologies as a power-law function of cumulative production.

$$Ccum_i = C_{0,i} * (Pcum_i)^{b_i} \tag{1}$$

In this equation, $Ccum_i$ represents the price or costs at the cumulative production $Pcum_i$. The price or costs of the first unit produced is defined as $C_{o.i}$, while b_i is the technology-specific experience index of technology i (in this case, SAF alternative i). The resulting logarithmic function gives a linear experience curve that can be plotted with b_i as the slope parameter and log $C_{o,i}$ as the price or cost axis intercept.

A technology-specific process ratio (PR_i) and a learning rate (LR_i) can be calculated with the formulas below. The learning rate can be defined as the rate at which a technology's price or costs decreases with each doubling of cumulative production [11].

$$PR_i = 2^{b_i} \tag{2}$$

$$LR_i = 1 - PR_i = 1 - 2^{b_i} \tag{3}$$

A PR_i of 0.7 (or 70%) means that with every doubling of cumulative production, the production costs decline with 30%, which is defined as the learning rate LR_i. In most studies and industries, it is common to have a PR_i in between 0.7 and 0.9. However, the HEFA technology is already mature and needs a PR_i of 1 [53] [54] [55].

V. CONCEPTUAL MODEL

This model aims to give a clear visual representation of the model's components and how these components are linked to each other. The development of the model is inspired by the CO_2 emissions forecasting method from ATAG (Figure 2) [9].

The conceptual model (Figure 4) developed by the author is based on the ATAG-model [9], but some extra dimensions are added. The backcasting principle is an integral part of this model; the goal (or carbon reduction scenarios in this case) is determined after the effects of technology and operations (step 3). The "carbon reduction gap" then needs to be filled by introducing the effects of SAF and Market-Based Measures. Therefore, step 4 and 5 are done in a later phase.

The effects of SAF and the effects of Market-Based Measures both have sub-processes. In the first, the initial fuel selection in Table II in the Appendix is added. By determining the cumulative production, the price development can be calculated (experience curve). After calculating SAF quantities needed to reach goals, the NPV can be determined. In the latter, cost reductions of CORSIA and EU-ETS are added (due to less fossil fuel use), and voluntary carbon credit costs are added if SAF can't close the carbon gap. This leads to a total NPV.

It is assumed that the conceptual model takes the COVID-19 crisis into account in the traffic forecast. Secondly, the conceptual model assumes that all SAF alternatives are technically ready and certified to use. Besides that, it is assumed that the introduction of SAF is the primary process to limit CO_2

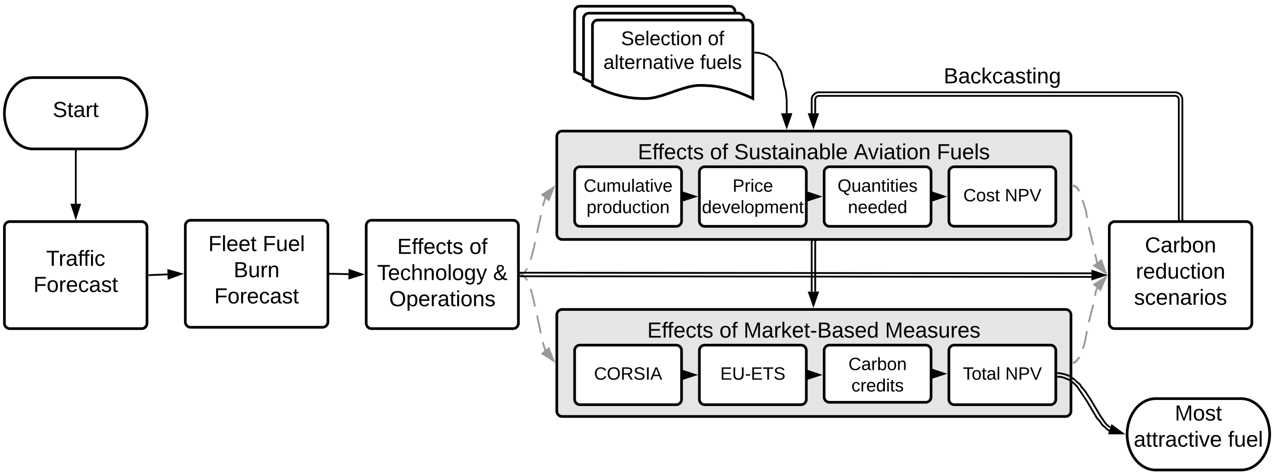


Fig. 4: Conceptual Model. Grey intermittent arrows are not active anymore, replaced by double black arrows.

emissions compared to the addition of emissions reductions from other sectors.

The first input is the traffic data that will be used in the first step. Secondly, percentages will be used that indicate the technological and operational efficiency improvements in step 3. A significant input component is the addition of SAF alternatives to the model in step 4. The main output will be the Net Present Value (NPV) of SAF alternatives.

The calculations and equations in the model can be found in section XI of the Appendix.

VI. COMPUTERISED MODEL

Next, the computerised model has been created. The equations discussed above are used in this model, which is made in Microsoft Excel.

A. *Traffic Forecast*

The traffic forecast starts with the use of Equation 4 to determine the RPK values per flight. A data-set of 155,449 flights executed in 2019 has been used to perform this analysis (confidential data). Equation 5 is used to determine the total RPK values per market i.

As discussed earlier, it is ambiguous to use global annual growth rates for aviation in a case study scenario, because upcoming Asian markets influence that growth rate. ICAO indicates expected growth curves per market [26]. These growth rates can be found in Table I and are used in Equation 6.

In section IV, a study has been performed into the aviation's expected recovery year. Assuming that tourism demand will recover sooner than aviation in general (that includes business traffic), the recovery year in the model is set at 2023 for now.

The years before the recovery year (e.g. 2020-2022) will get a standard value 0 for RPK demand. There are three main reasons to use this limitation. At first, demand during the COVID-19 recovery period is practically impossible to forecast due to external factors, such as possible new COVID-19 infection waves, closed borders, and other travel-restricting policies. Besides that, one can assume that airlines won't invest large amounts of money in crisis times. The third reason is the resulting CO_2 emissions in the recovery period will not equal the CORSIA baseline emissions of 2019, which means there is no financial incentive to invest in carbon reduction during the recovery period.

TABLE I: Compound Annual Growth Rates. Adapted from ICAO [26].

Market	30 year CAGR
Intra Europe	2.6%
Europe ↔ Central America / Caribbean	3.8%
Europe ↔ Central and South-West Asia	5.1%
Europe ↔ Middle East	4.0%
Europe ↔ North Africa	4.1%
Europe ↔ North America	2.6%
Europe ↔ Pacific South-East Asia	4.4%
Europe ↔ South America	4.1%
Europe ↔ Sub Saharan Africa	2.8%

The result of this process is a demand forecast for the period 2020-2050 that is specified into different markets. A summation of these market demands gives the total demand forecast.

B. *Fleet fuel burn forecast*

The next step is to estimate the fuel burn and the resulting emissions from the demand forecast with the use of Equation 7 and Equation 8. TUI Aviation works with company-wide CO_2/RPK values to measure carbon efficiency, but it is more accurate to calculate the CO_2/RPK per market i (used data is confidential). For instance, longer flights mostly have a lower CO_2/RPK, because the relatively high amount of fuel burned during take-off has a lower share in the total flight compared to short flights. The result of this process is a summation of all CO_2 emissions per year.

C. Effects of Technology & Operations

In section IV, the technological and operational efficiency improvements have been discussed. Decided was to use a 1% per year technological efficiency improvement, which refers to introducing more efficient aircraft that replace less fuel-efficient ones. Operational improvement is estimated at 6% in total until 2050, which can be achieved by, i.e. better Air Traffic Management. Equation 9 and Equation 10 are implemented in Excel to determine the CO_2 after technological and operational efficiency improvements.

D. Carbon reduction scenarios

Before the effects of alternative fuels can be measured, it is needed to know how many carbon emissions need to be mitigated.

The first scenario is to limit the carbon emissions to 50% of the levels emitted in 2005. However, no reliable data of TUI's 2005 operations can be found. Therefore, the share of TUI's aviation emissions within the global aviation emissions in 2019 is extrapolated to 2005. The total emissions of TUI in 2019 were 5.3 Mt (TUI data), while the global aviation emissions were 914 Mt [56]. Considering that global aviation accounted for 733 Mt in 2005 [24], an extrapolation of TUI's share results in 4.2 Mt. A 50% reduction of this level gives a 2.1 Mt carbon emission goal for 2050.

The net-zero emission scenario is the second and most rigorous scenario. Instead of emitting a maximum of 2.1 Mt of CO_2, it is the goal to keep the emission levels in 2050 at 0 Mt.

With the use of Equation 11 till Equation 16, the two carbon reduction scenarios can be calculated, which can be seen in tab A5 of the model. The result is that the two scenarios described above have stated the minimum carbon mitigation for all years in the period 2020-2050.

E. Effects of Sustainable Aviation Fuels

These are extracted from a list from ICAO [51]. The conversion processes in this list comply with ASTM criteria, and the feedstocks are accepted by ICAO to be used for CORSIA carbon reduction. The input data can be found in Table IV in the Appendix.

Life cycle assessment values are given by ICAO, which depicts Core LCA values and iLUC LCA values. The first refers to the actual CO_2 that is emitted by the fuel, while iLUC refers to the indirect (or induced) Land Use Change. These values are high for, i.e. palm oil, because land area is extracted from food production to grow palm, which has a negative indirect effect on the environment and society. The combination of Core LCA and iLUC LCA gives a total LSf, which is calculated in $gCO2e/MJ$. (=89g for fossil fuel).

1) Cumulative production: The first step to determine the most attractive fuel in a business perspective is to determine future SAF production for each producer and specified by conversion process and feedstock used. This includes diesel production because this fuel can be produced with the same conversion processes and feedstocks, which complement the experience curve theory. Although this overview may not be fully complete or accurate (because producers may not communicate their entire strategy to the public), it gives an overview of production growth for the next 5 to 10 years. The fuel production quantities are summed with Equation 19 to retrieve cumulative production values.

2) Price Development: The next step is to use the cumulative production quantities to determine future prices. The different sources could not be compared easily due to different research methods and years in which the research was executed. Therefore, there has been chosen to apply a weighted average to determine the MSP that will be used in the analysis, assuming the most recent research will show the most accurate results. The oldest source [48] gets a weight of 1, while an extra year will receive an extra value 1, which ensures that [49] and [50] both receive a weight of 7. The results can be found in Table II. These weighted average prices will be used as input in the model (as $C_{i,2020}$ within Equation 20).

3) Quantities needed: First, it is needed to calculate the SAF quantities required to reach the CO_2 reduction goals of the two scenarios. By using the percentage of CO_2 reduction for each year and the expected total emissions after technological and operations improvements, the estimated total CO_2 reduction can be calculated. After that, the fuel alternatives' emissions reduction factor is used to determine the quantity of fuel needed for all fuel alternatives. This is done with the help of Equation 21. These calculations for all years t from 2020 to 2050, and all fuel alternatives i, will create a fuel quantity road-map for both scenarios s.

4) Cost NPV: After determining the fuel quantities needed to reach the scenario goals, it is necessary to calculate the costs of implementing the alternative fuels. The total cost per year is calculated with Equation 22. The cost reduction of acquiring fossil fuel is included in this equation. The latter is specified at 362.33 USD/ton due to a 36-month Moving Average forecast of jet fuel prices [57].

F. Effects of Market-Based Measures

The next step in this analysis is to analyse the effects of Market-Based Measures on the overall outcome.

Without introducing SAF, TUI Aviation should have paid EU-ETS and CORSIA credits over all fuel and flights that they would have needed from 2020 to 2050, if these flights are relevant under the specific schemes (i.e. CORSIA is only for international flights and EU-ETS only for Intra-EER flights). However, the introduction of SAF ensures that there will be less net carbon emissions. Thus there will be a decrease in costs related to these two mandatory carbon mitigation schemes. The yearly totals will be summed using an extra NPV, which results in an NPV cost reduction of 182.8 million USD for the 50% reduction scenario and 199.4 million USD for the net-zero scenario. This is equal for all fuel alternatives because the carbon reduction per year is the same for all alternatives.

During this analysis, it seemed that some SAF alternatives did not have enough carbon mitigation per metric tonne of

SAF to reach the goals fully. The left-over carbon emissions that need to be mitigated to reach the goals need to be offset via voluntary carbon offsetting. These carbon credits cost approximately 10 USD per metric tonne of CO_2. Assuming TUI Aviation needs to offset all carbon emissions that limit them from reaching their goals, these will be credited in this model.

VII. VERIFICATION AND VALIDATION

The verification contained model components testing and unit testing, while validation did acceptance testing and data validation.

The latter validates the literature and data used in the model. The model contains a lot of information that is assumed to be reliable, but some are more reliable than others. Each main data component is stated in Table V in the Appendix, that states the reliability of sources, the usability of the data, and comments when necessary.

A sensitivity analysis indicated that the discount rate, the process ratio, and the minimum selling price are the most sensitive parameters in the model.

VIII. RESULTS

With the CAGR from Table I, the expected forecast for 2023 (the recovery year) is 79 million RPK, which grows to 181 million RPK in 2050. A resulting graph can be found in Figure 5.

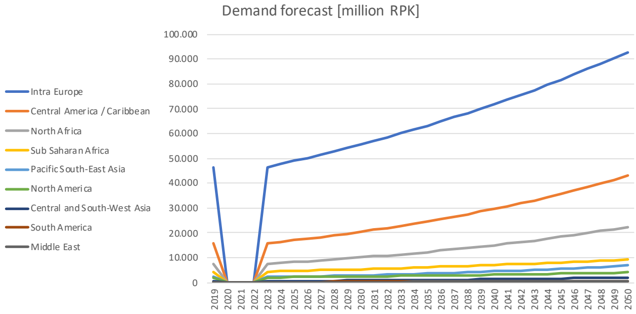


Fig. 5: Demand forecast for TUI Aviation in 2020-2050 in million Revenue Passenger Kilometers

In the ”Business-as-Usual” or ”No-action” scenario, the carbon emissions of TUI Aviation will grow to 12.07 Mt of CO_2 per year in 2050. CORSIA relevant flights will be 8.78 Mt (yellow and grey), while EU-ETS will be 5.46 Mt (yellow and orange). To give a visual explanation of EU-ETS and CORSIA relevance among flights, a distribution can be seen in Figure 6.

In 2050, a 3.23 million ton technology improvement and a 0.71 Mt operational improvement are expected. Subtracting these from the ”No Action” scenario (12.07 Mt) results in a new CO_2 emission forecast of 8.13 Mt (the blue area in Figure 7).

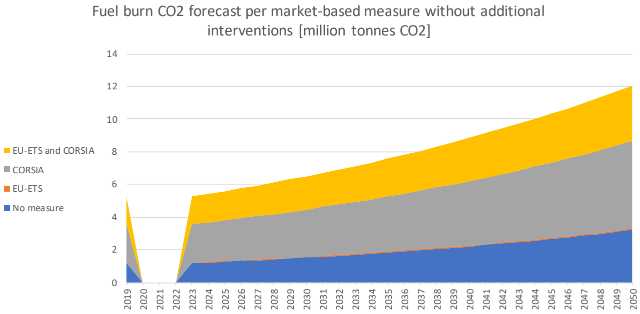


Fig. 6: CO_2 forecast for TUI Aviation in 2020-2050 in million metric tonnes of CO_2 per MBM

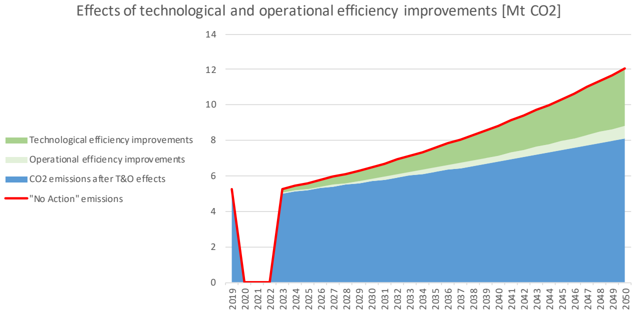


Fig. 7: The effects of technological and operational efficiency improvements on the fuel burn CO_2 forecast of TUI Aviation

A graphical representation of the carbon reduction scenarios can be seen in Figure 8 with reduction start level 1.0% in the start year 2023. The 50% reduction scenario requires a maximum of 2.11 Mt of CO_2 in 2050. Starting in 2023 with 1% reduction requires a 17.3% annual growth factor in carbon mitigation. The net-zero scenario will lead to no emissions in 2050, using a start in 2023, and 1% carbon reduction requires an 18.6% annual growth factor in carbon mitigation.

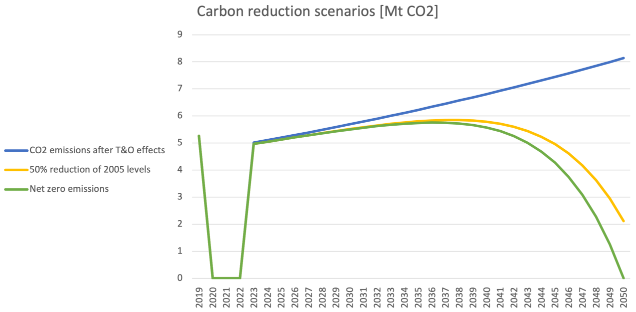


Fig. 8: Scenario forecast for TUI Aviation in 2020-2050

Then, the cumulative production of SAF alternatives has been calculated. This results in the following production forecast in Figure 9. The figure gives a clear view of several alternatives’ production forecast, with HEFA-SPK from Used Cooking Oil and Tallow being the most produced fuels in the coming years. This could be due to the maturity of the HEFA production process. In total, we can expect more than 13 million tonnes of renewable fuels to be produced in 2025, while current production is almost 5 Mt. One major drawback of this overview is that not all production increases are included, especially in the period 2025-2030.

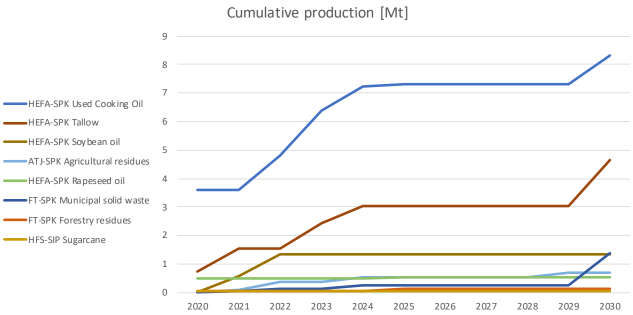


Fig. 9: Cumulative production of fuel alternatives (in Mt), only showing the alternatives with known production quantities and including diesel fuels

The experience curve theory was used to determine future prices of SAF alternatives. The cumulative production of these alternatives was used as input in this analysis. Using a PR_i of 1 for HEFA fuels and 0.9 for other fuels results in Figure 10.

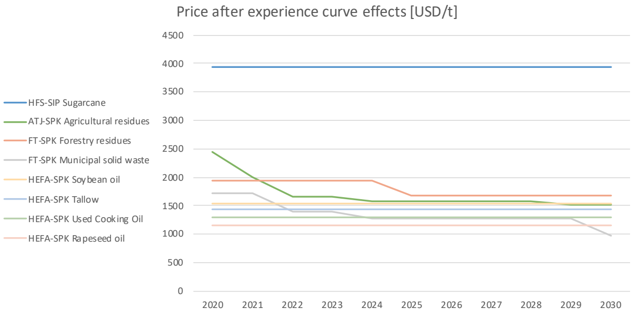


Fig. 10: Cost of fuel alternatives after experience curve effects (in USD/ton)

This graph shows that HEFA fuels have a constant price between 2020 and 2030 (due to the $PR_i = 1$), while others have a decreasing price. One of the outstanding alternatives is FT-SPK of Municipal Solid Waste, starting at 1729 USD/ton in 2020 and ending at 980 USD/ton in 2030. ATJ-SPK with Agricultural Residues also decreases proportionally, with 2442 USD/ton in 2020 and 1521 USD/ton in 2030.

After determining the offtake quantities of each SAF alternative, these offtake quantities per year could be used with the future prices to calculate the implementation costs per year. The cost reduction of fossil fuel purchasing and cost reduction of Market-Based Measures are included in this calculation.

The analysis gives the Total NPV as a result for all 22 SAF alternatives that are ASTM certified (and thus technically ready to use). However, not all of these alternatives have a cumulative production planned in the coming years. Therefore, 14 SAF alternatives need to be excluded for now. Besides that, some SAF alternatives do not comply with stakeholder policies and goals. As discussed in section IV, fuels may not be a first-generation fuel, because these feedstocks interfere with food production. This eliminates a further 3 SAF alternatives from the selection. This leaves five eligible fuels for this research. The overview of these fuels can be found in Figure 11.

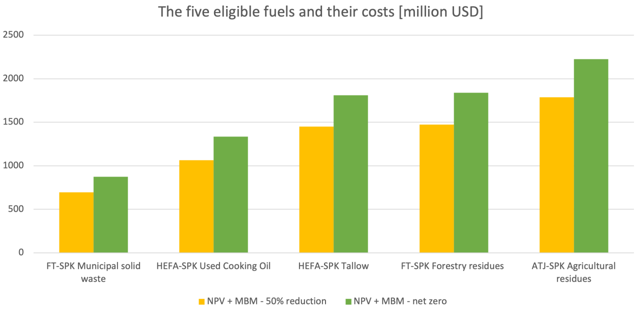


Fig. 11: The resulting fuels that could be implemented in TUI Aviation operations

IX. Conclusion

The FT-SPK fuel made from Municipal Solid Waste is most cost-efficient from a business perspective, taking into account all regulations and goals. To reach the 50% reduction scenario, the company needs to invest 695 million USD (Net Present Value), resulting in an 89% minimum blending percentage of SAF, which means that 11% could still be fossil fuel while reaching the goal. For the net-zero scenario, an investment of 875 million USD is needed, and the blending percentage will be 120%, which is not possible. Therefore, 100% SAF is required in this scenario, while the left-over carbon emissions will be offset by acquiring carbon credits in other sectors.

X. Discussion

This research has brought valuable insights into the techno-economic implementation of SAF. By combining a traffic forecast and resulting CO_2 emissions forecast for the period until 2050, a price development analysis using the experience curve, and the fill of the carbon reduction gap (to reach goals) with the implementation of SAF, a coherent and usable conclusion can be made.

One of the strengths of this research is the differentiation of SAF alternatives and their characteristics; each alternative has its own price and carbon mitigation potential. Therefore, cheap SAF alternatives (such as HEFA-SPK made from palm oil) do not necessarily lead to a low investment cost, because the carbon mitigation power is low and, therefore, more SAF quantities are needed to realise a certain reduction. One other important insight is the influence of price development (using the experience curve) on the results. Without the use of the experience curve analysis, HEFA-SPK from Used Cooking Oil would be the most attractive alternative in a business perspective (as discussed in sensitivity analysis). However, the use of the experience curve ensured FT-SPK from Municipal Solid Waste to be more attractive.

However, one major weakness of this research is that scientific knowledge on SAF minimum selling prices seems to be limited. Sources indicate a wide range of prices for SAF alternatives, which makes it difficult to give a reliable estimate or average that can be used as input in the model. Another weakness of the research is the poor reliability and usability of SAF production quantity data. The cumulative production of SAF alternatives is a major component in the determination of the SAF prices (with the experience curve method). A final weakness is the usage of Compound Annual Growth Rates (CAGR) to determine future air traffic demand. Although the data seem to be reliable, unforeseen changes in travel behaviour by consumers can influence the growth rate.

Although the research focused on the business perspective of TUI Aviation, this could be generalised toward the aviation sector in general. The two TUI-specific input parameters are the demand input of 2019 and the CAGRs which are related to the markets of TUI Aviation. However, changing these parameters does not give any other results in general, except the height of the Net Present Value of investment. For instance, changing the CAGR to another (i.e. negative) value or changing the demand input data, still results in FT-SPK from Municipal Solid Waste as being the most attractive fuel in a business perspective.

XI. RECOMMENDATIONS

The future prices of alternative fuels have been determined using the experience curve theory, but other monetary values play a role. Future research could focus on the future prices of fossil fuel (now it is set at a fixed price for the entire forecasting period). Besides that, carbon mitigation schemes such as CORSIA and EU-ETS could become more expensive in the future. Including price fluctuations and/or trends would be beneficial to the model and the outcomes' reliability.

One of the significant drawbacks of this research was that information about alternative fuels' prices was very hard to find. Relying on academic publishing is the only way to accomplish that because producers won't communicate their prices publicly due to confidentiality agreements with clients and not to enrich competitors with pricing information. Any new data availability developments would strengthen this model and the outcomes, mainly because the price inputs are a very sensitive parameter in the model.

It was very difficult to determine the fuels' future cumulative production, and used sources were not at an academic level, but mostly news articles and producers' websites. Besides that, some producers may keep their production targets confidential. The growth in cumulative production affects the experience curve used, and thus future prices of fuels. Therefore, updating and completing the Producers overview would benefit the model significantly.

Only fuels are included at the moment that already passed technological readiness tests and certifications. However, R&D is not at a standstill, and carbon-free fuels could be the future. One of the proposed technologies is Power-to-Liquid, including the capture of carbon emissions from the air that are converted into zero-carbon fuels. Because certification will take another couple of years and little about characteristics and pricing has been known publicly yet, it is better to wait and include these fuels later.

Finally, SAF implementation would have no or little influence on radiative forcing caused by contrails [58]. However, future research may object that statement, especially because there is still a large scientific uncertainty around the effects of contrails on global warming. When new information is available, it would be useful to include the effects of contrails into this model in further research.

SUPPLEMENTARY DATA

Supplementary data and the computerised model associated with this article can be requested by sending an email to author K.J.P. van Bentem (koenvanbentem@gmail.com).

REFERENCES

[1] M. Mazraati, "World aviation fuel demand outlook," *OPEC Energy Review*, vol. 34, no. 1, pp. 42–72, 3 2010.

[2] M. Grote, I. Williams, and J. Preston, "Direct carbon dioxide emissions from civil aircraft," *Atmospheric Environment*, vol. 95, pp. 214–224, 10 2014.

[3] M. D. Staples, R. Malina, P. Suresh, J. I. Hileman, and S. Barrett, "Aviation CO2 emissions reductions from the use of alternative jet fuels," *Energy Policy*, vol. 114, pp. 342–354, 2018.

[4] ICAO, "Trends in Emissions that affect Climate Change," Montreal. [Online]. Available: https://www.icao.int/environmental-protection/Pages/ClimateChange_Trends.aspx

[5] P. S. Nigam and A. Singh, "Production of liquid biofuels from renewable resources," *Progress in Energy and Combustion Science*, vol. 37, no. 1, pp. 52–68, 2 2011.

[6] E. Martinez-Hernandez, L. F. Ramírez-Verduzco, M. A. Amezcua-Allieri, and J. Aburto, "Process simulation and techno-economic analysis of bio-jet fuel and green diesel production — Minimum selling prices," *Chemical Engineering Research and Design*, vol. 146, pp. 60–70, 6 2019.

[7] W. F. Mustapha, T. F. Bolkesjø, T. Martinsen, and E. Trømborg, "Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning," *Energy Conversion and Management*, vol. 149, pp. 368–380, 2017.

[8] N. R. Baral, O. Kavvada, D. Mendez-Perez, A. Mukhopadhyay, T. S. Lee, B. A. Simmons, and C. D. Scown, "Techno-economic analysis and life-cycle greenhouse gas mitigation cost of five routes to bio-jet fuel blendstocks," *Energy & Environmental Science*, vol. 12, no. 3, pp. 807–824, 2019.

[9] Air Transport Action Group, "Waypoint 2050. Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency," Air Transport Action Group, Tech. Rep., 2020.

[10] IATA, "IATA Sustainable Aviation Fuel Roadmap," IATA, Tech. Rep., 2015.

[11] M. Weiss, M. Junginger, M. K. Patel, and K. Blok, "A review of experience curve analyses for energy demand technologies," *Technological Forecasting and Social Change*, vol. 77, no. 3, pp. 411–428, 2010.

[12] ICAO, "What is CORSIA and how does it work?" Montreal. [Online]. Available: https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx

[13] European Commission, "Reducing emissions from aviation — Climate Action." [Online]. Available: https://ec.europa.eu/clima/policies/transport/aviation_en

[14] A. van Velzen, S. de Bruyn, and A. Bachaus, "Costs of EU ETS and CORSIA for European aviation," CE Delft, Tech. Rep., 11 2019.

[15] G. Squadrin and F. Schmit, "Europe makes legislative push for aviation transition," 9 2020. [Online]. Available: https://www.argusmedia.com/en/news/2145902-europe-makes-legislative-push-for-aviation-transition

[16] Biofuels FlightPath, “Swedish proposal for a sustainable aviation fuel mandate in Sweden,” 3 2019. [Online]. Available: https://www.biofuelsflightpath.eu/news/60-swedish-proposal-for-an-alternative-aviation-fuel-mandate-in-sweden

[17] Ministerie van IenW, “Minister Van Nieuwenhuizen imposes use of cleaner fuel in aviation sector,” 3 2020. [Online]. Available: https://www.government.nl/latest/news/2020/03/04/minister-van-nieuwenhuizen-imposes-use-of-cleaner-fuel-in-aviation-sector

[18] K. Soubly, C. Wolff, L. Uppink, D. Riefer, C. Kienzler, A. Dichter, D. Pinner, R. Riede, T. Melgin, A. Mucha, C. Vernet, and H. Göthel, “Clean Skies for Tomorrow. Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation,” World Economic Forum, McKinsey & Company, Tech. Rep. November, 2020.

[19] HM Government, “The Ten Point Plan for a Green Industrial Revolution,” HM Government, Tech. Rep., 2020.

[20] K. Nilson and A. Tuvlind, “Carbon Offsetting and Sustainable Aviation: A study of contemporary and future sustainable aviation via carbon offsetting,” Ph.D. dissertation, KTH Royal Institute of Technology, 2020.

[21] ICAO, “CORSIA Eligible Emissions Units,” ICAO, Tech. Rep. August, 2020. [Online]. Available: https://www.icao.int/environmental-protection/CORSIA/Documents/TAB/TAB2020/ICAO_Doc_CORSIA_Eligible_Emissions_Units_March_2020.pdfhttps://www.icao.int/environmental-protection/CORSIA/Documents/TAB/TAB2020/ICAO_Doc_CORSIA_Eligible_Emissions_Units_March_

[22] oneworld Alliance, “oneworld member airlines commit to net zero carbon emissions by 2050,” 2020. [Online]. Available: https://www.oneworld.com/news/2020-09-11-oneworld-member-airlines-commit-to-net-zero-carbon-emissions-by-2050

[23] B. H. Archer, “Forecasting demand,” *International Journal of Tourism Management*, vol. 1, no. 1, pp. 5–12, 3 1980.

[24] D. S. Lee, D. W. Fahey, P. M. Forster, P. J. Newton, R. C. Wit, L. L. Lim, B. Owen, and R. Sausen, “Aviation and global climate change in the 21st century,” *Atmospheric Environment*, vol. 43, no. 22-23, pp. 3520–3537, 7 2009.

[25] M. Janić, “Greening the Airport Airside Area II: Liquid Hydrogen as an Alternative Fuel,” in *Green Energy and Technology*. Springer-Verlag London Limited, 2011, vol. 52, pp. 133–163.

[26] ICAO, “ICAO Long-Term Traffic Forecasts Passenger and Cargo,” ICAO, Tech. Rep., 2018.

[27] R. Ali, “What Shape Would the Travel Industry Recovery Look Like?” 4 2020. [Online]. Available: https://skift.com/2020/04/12/what-shape-would-the-travel-industry-recovery-look-like/

[28] J. Jolly, “Airlines may not recover from Covid-19 crisis for five years, says Airbus,” 4 2020. [Online]. Available: https://www.theguardian.com/business/2020/apr/29/airlines-may-not-recover-from-covid-19-crisis-for-five-years-says-airbus

[29] M. Unnikrishnan, “Don’t Count on Airlines to Recover for 3 Years,” 4 2020. [Online]. Available: https://skift.com/2020/04/22/dont-count-on-airlines-to-fully-recover-for-3-years-delta-ceo/

[30] Luchtvaartnieuws, “1,3 miljard euro verlies verwacht voor Air France-KLM,” 10 2020. [Online]. Available: https://www.luchtvaartnieuws.nl/nieuws/categorie/2/airlines/13-miljard-euro-verlies-verwacht-voor-air-france-klm

[31] ——, “’Lufthansa overweegt geheel afscheid te nemen van A380, A340 en 747-400’,” 8 2020. [Online]. Available: https://www.luchtvaartnieuws.nl/nieuws/categorie/2/airlines/lufthansa-overweegt-geheel-afscheid-te-nemen-van-a380-a340-en-747-400

[32] Simple Flying, “Emirates Could Take Until 2024 To Return To Normal,” 6 2020. [Online]. Available: https://simpleflying.com/emirates-2024-normality/

[33] Luchtvaartnieuws, “Coronacrisis en afschrijvingen drukken IAG in het rood,” 7 2020. [Online]. Available: https://www.luchtvaartnieuws.nl/nieuws/categorie/2/airlines/coronacrisis-en-afschrijvingen-drukken-iag-in-het-rood

[34] ——, “TUI-directeur Arjan Kers rekent op volledig herstel in 2022,” 8 2020. [Online]. Available: https://www.luchtvaartnieuws.nl/nieuws/categorie/72/algemeen/tui-directeur-arjan-kers-rekent-op-volledig-herstel-in-2022

[35] NU.nl, “TUI-baas optimistisch over 2021 en verwacht een ’grotendeels normale zomer’,” 1 2021. [Online]. Available: https://www.nu.nl/economie/6099847/tui-baas-optimistisch-over-2021-en-verwacht-een-grotendeels-normale-zomer.html

[36] H. M. Noh, A. Benito, and G. Alonso, “Study of the current incentive rules and mechanisms to promote biofuel use in the EU and their possible application to the civil aviation sector,” *Transportation Research Part D: Transport and Environment*, vol. 46, no. 2016, pp. 298–316, 7 2016.

[37] P. Peeters, J. E. S. Higham, D. Kutzner, S. A. Cohen, and S. Gössling, “Are technology myths stalling aviation climate policy?” *Transportation Research Part D: Transport and Environment*, vol. 44, pp. 30–42, 5 2016.

[38] S. Sgouridis, P. A. Bonnefoy, and R. J. Hansman, “Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation,” *Transportation Research Part A: Policy and Practice*, vol. 45, no. 10, pp. 1077–1091, 12 2011.

[39] O. Zaporozhets, V. Isaienko, and K. Synylo, “Trends on current and forecasted aircraft hybrid electric architectures and their impact on environment,” *Energy*, vol. 211, p. 118814, 11 2020.

[40] EASA, “European Aviation Environmental Report 2019,” EASA, EEA, EUROCONTROL, Tech. Rep. 1, 2019. [Online]. Available: https://www.eurocontrol.int/publication/european-aviation-environmental-report-2019

[41] J. Morris, A. Rowbotham, A. Angus, M. Mann, and I. Poll, “A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector. OMEGA Project 14 – Final Report,” Cranfield University, Bedford, Tech. Rep. January, 2009.

[42] IATA, “Fuel Fact Sheet,” IATA, Tech. Rep., 2020. [Online]. Available: https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-fuel.pdf

[43] Dutch Emissions Authority, “Updated monitoring rules for EU-ETS and CORSIA.” [Online]. Available: https://www.emissionsauthority.nl/topics/general---ets-aviation-and-corsia/updated-monitoring-rules-for-eu-ets-and-corsia

[44] M. Janić, “An assessment of the potential of alternative fuels for “greening” commercial air transportation,” *Journal of Air Transport Management*, vol. 69, pp. 235–247, 6 2018.

[45] ICAO, “Sustainable Aviation Fuels Guide,” ICAO, Montreal, Tech. Rep., 2017. [Online]. Available: www.icao.int/environmental-protection/Pages/ICAO_UNDP.aspx

[46] A. W. Schäfer, “The Prospects for Biofuels in Aviation,” in *Biofuels for Aviation*. Elsevier, 2016, pp. 3–16.

[47] IATA, “Fact Sheet 2: SAF Technical Certification,” IATA, Tech. Rep., 2019.

[48] M. D. Staples, R. Malina, H. Olcay, M. N. Pearlson, J. I. Hileman, A. Boies, and S. R. H. Barrett, “Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies,” *Energy Environ. Sci.*, vol. 7, no. 5, pp. 1545–1554, 2014.

[49] R. S. Capaz, E. Guida, J. E. A. Seabra, P. Osseweijer, and J. A. Posada, “Mitigating carbon emissions through sustainable aviation fuels: costs and potential,” *Biofuels, Bioproducts and Biorefining*, p. bbb.2168, 11 2020.

[50] N. Vela-García, D. Bolonio, A. M. Mosquera, M. F. Ortega, M.-J. García-Martínez, and L. Canoira, “Techno-economic and life cycle assessment of triisobutane production and its suitability as biojet fuel,” *Applied Energy*, vol. 268, no. March, p. 114897, 6 2020.

[51] ICAO, “CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels,” ICAO, Montreal, Tech. Rep., 2019.

[52] G. Festel, M. Würmseher, and C. Rammer, “Scaling and Learning Effects of Biofuels Conversion Technologies,” *Energy Technology*, vol. 2, no. 7, pp. 612–617, 2014.

[53] R. Mawhood, E. Gazis, S. de Jong, R. Hoefnagels, and R. Slade, “Production pathways for renewable jet fuel: a review of commercialization status and future prospects,” *Biofuels, Bioproducts and Biorefining*, vol. 10, no. 4, pp. 462–484, 7 2016.

[54] W. R. Cervi, R. A. C. Lamparelli, J. E. A. Seabra, M. Junginger, S. Jong, and F. Hilst, “Spatial modeling of techno-economic potential of biojet fuel production in Brazil,” *GCB Bioenergy*, vol. 12, no. 2, pp. 136–157, 2 2020.

[55] M. Leila, J. Whalen, and J. Bergthorson, “Strategic spatial and temporal design of renewable diesel and biojet fuel supply chains: Case study of California, USA,” *Energy*, vol. 156, no. 2018, pp. 181–195, 8 2018.

[56] Air Transport Action Group, “Aviation Benefits Beyond Borders. Powering global economic growth, trade links, tourism and support for

sustainable development through air transport, despite global crisis." Air Transport Action Group, Tech. Rep., 2020.

[57] IndexMundi, "Jet fuel daily price," 2020. [Online]. Available: https://www.indexmundi.com/commodities/?commodity=jet-fuel

[58] F. Caiazzo, A. Agarwal, R. L. Speth, and S. R. Barrett, "Impact of biofuels on contrail warming," *Environmental Research Letters*, vol. 12, no. 11, p. 114013, 11 2017.

[59] ICAO, "ICAO Environmental Report 2019: Destination Green. The Next Chapter," ICAO, Montreal, Tech. Rep., 2019.

[60] S. J. Bann, R. Malina, M. D. Staples, P. Suresh, M. Pearlson, W. E. Tyner, J. I. Hileman, and S. Barrett, "The costs of production of alternative jet fuel: A harmonized stochastic assessment," *Bioresource Technology*, vol. 227, pp. 179–187, 2017.

[61] S. de Jong, R. Hoefnagels, A. Faaij, R. Slade, R. Mawhood, and M. Junginger, "The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison," *Biofuels, Bioproducts and Biorefining*, vol. 9, no. 6, pp. 778–800, 11 2015.

[62] ICAO, "Estimated Prices of Aviation Alternative Fuels," ICAO, Tech. Rep., 2017. [Online]. Available: https://www.icao.int/Meetings/CAAF2/Documents/CAAF.2.WP.008.1.en.Estimated%0Aprices%0Aof%0AAAF.FINAL.pdf

[63] X. Li, E. Mupondwa, and L. Tabil, "Technoeconomic analysis of biojet fuel production from camelina at commercial scale: Case of Canadian Prairies," *Bioresource Technology*, vol. 249, no. September 2017, pp. 196–205, 2 2018.

[64] A. N. Pavlenko, S. Searle, and A. Christensen, "The cost of supporting alternative jet fuels in the European Union," International Council on Clean Transportation, Tech. Rep. March, 2019.

[65] H. Wei, W. Liu, X. Chen, Q. Yang, J. Li, and H. Chen, "Renewable bio-jet fuel production for aviation: A review," *Fuel*, vol. 254, p. 115599, 10 2019.

[66] W.-C. Wang, L. Tao, J. Markham, Y. Zhang, E. Tan, L. Batan, M. Biddy, W.-C. Wang, L. Tao, Y. Zhang, E. Tan, E. Warner, and M. Biddy, "Review of Biojet Fuel Conversion Technologies," National Renewable Energy Laboratory, Tech. Rep. July, 2016. [Online]. Available: https://www.nrel.gov/docs/fy16osti/66291.pdf

Appendix

APPENDIX A - CALCULATIONS IN THE MODEL

The components in the conceptual model mainly consist of calculations. The output of a model component is generally the result of calculations that have been done within that model component. The output of model components generally is input for the next model component.

A. Traffic forecast

At first, the RPK values (a standard KPI for demand) are determined. The RPK per flight can be calculated by multiplying the distance with the number of revenue passengers:

$$RPK_j = d_j * RP_j \tag{4}$$

Where RPK_j is the RPK for flight j, d_j is the distance of flight j in kilometres, and RP_j is the number of Revenue Passengers in flight j. The RPK of all flights is then summed, either for all flights or per attribute (such as per market i below):

$$F_{i,0} = \sum_{j=0}^{\infty} RPK_j \qquad \forall j \in i \tag{5}$$

Where $F_{i,0}$ is the RPK forecast for market i in year $t = 0$. Then, Compound Annual Growth Rates are used to determine the demand in future years. The CAGR is implemented in the following formula:

$$F_{i,t} = F_{i,t-1} * (1 + CAGR_i) \tag{6}$$

Where $F_{i,t}$ is the RPK forecast for market i in year t, and $CAGR_i$ is the Compound Annual Growth Rate per market i. The demand forecast $F_{i,t}$ is the output of this model component.

B. Fleet fuel burn forecast

The demand forecast output of the previous component will be transformed into a CO_2 forecast in this component. Therefore, a carbon efficiency KPI can be used: CE_i, which is the carbon efficiency in CO_2/RPK per market i. This variable is implemented in the following variables:

$$E_{i,t} = F_{i,t} * CE_i \tag{7}$$

$$E_t = \sum_{i=0}^{\infty} E_{i,t} \qquad \forall t \in [2020, 2050] \tag{8}$$

Where $E_{i,t}$ is the CO_2 emissions of market i in year t, $F_{i,t}$ is the demand forecast of market i in year t, and CE_i is the carbon efficiency of market i (in CO_2/RPK). A summation of $E_{i,t}$ in Equation 8 gives the total carbon emissions E_t per year as output in this model component.

C. Effects of Technology & Operations

Efficiency improvements from technology and operations will limit future CO_2 emissions in commercial aviation. These efficiency improvements will be deducted from the output E_t in the previous component by executing the formulas below:

$$OE = (1 + TOE)^{\frac{1}{30}} - 1 \tag{9}$$

$$EL_t = E_t * (1 - TE - OE)^{t-2019} \tag{10}$$

Where TOE is the Total Operational Efficiency improvement (in 30 years), OE is the Operational Efficiency improvement per year, TE is the Technological Efficiency improvement per year, and EL_t is the Emission Level in year t (after technological and operational efficiency improvements). The output of this model component is the EL_t.

D. Carbon reduction scenarios

Input for this model component is the EL_t calculated above. Besides that, a carbon mitigation start level and start year need to be determined by the user, that will be used as input (e.g., start with 1 % carbon mitigation in start year 2023).

In this model component, an annual growth factor of the chosen start level and year is calculated with the following formulas:

$$EG_{s,t} = EL_t * (1 - RP_{s,t}) \tag{11}$$

Where $EG_{s,t}$ is the Emission Goal for scenario s in year t, EL_t is the Emission Level in year t (after technological and operational efficiency improvements), and $RP_{s,t}$ is the

Reduction Percentage for scenario s in year t. This can be rewritten in the following formula:

$$RP_{s,t} = 1 - \frac{EG_{s,t}}{EL_t} \tag{12}$$

With the availability of the Reduction Factor in 2050 and the start year and quantity of the mitigation project, the annual growth factor can be calculated:

$$GF_s = {\frac{RP_{s,2050}}{RP_{s,SY_s}}}^{\frac{1}{2050-SY_s}} - 1 \tag{13}$$

Where GF_s is the Growth Factor of scenario s, $RP_{s,2050}$ is the Reduction Factor in 2050, RP_{s,SY_s} is the Reduction Percentage in starting year SY_s.

This Growth factor can calculate the annual carbon mitigation for all years until 2050. But to ensure that the resulting reduction factors comply with the governmental quota, for every s and t the maximum is taken of $RP_{s,t}$ and the governmental mandates or quota, to ensure that governmental quota are being met:

$$Q_t = \sum_{k=1}^{\infty} Q_{k,t} * FS_k \qquad \forall t \in [2020, 2050] \tag{14}$$

Where Q_t is the total quota in year t, $Q_{k,t}$ is the quota of country k in year t, and FS_k is the Fuel Share of departures in country k out of the total fuel consumption of the company. This gives the final formula for the Effective RP and Effective EG that take the governmental quota into account:

$$ERP_{s,t} = \max(RP_{s,t}; Q_t) \tag{15}$$

$$EEG_{s,t} = EL_t * (1 - ERP_{s,t}) \tag{16}$$

E. Effects of Sustainable Aviation Fuels

This model component consists of four sub-processes, which are explained below.

Selection of alternative fuels: First, the emission reduction power of fuels is calculated. The Emission Reduction factor ER can be calculated to determine the quantity of CO_2 that is reduced by using a specific fuel. The following formula is used by ICAO [59]:

$$ER_t = FCF * \left[\sum_{f=1}^{\infty} MS_{i,t} * \left(1 - \frac{LS_f}{LC}\right) \right] \qquad \forall t \in [2020, 2050] \tag{17}$$

Where ER_t is the emissions reduction factor in year t, FCF is the fuel conversion factor (fixed value, 3.16 for Jet A1 fuel [kg CO_2 / kg fuel]), $MS_{i,t}$ is the total mass of a CORSIA eligible fuel claimed in the year t by fuel type i (in tonnes), LSf is the life cycle emissions factor of the SAF alternative, and LC is the baseline life cycle emissions (fixed value, 89 for Jet A1 fuel [gCO2e/MJ]).

The formula is meant to calculate the total reduction for a given fuel offtake within an airline operator. But with $MS_{i,t} = 1$, the emissions reduction per tonne fuel can be determined.

To calculate the total carbon reduction potential of alternative fuels, the following formula is used:

$$CRP_i = \frac{\frac{FAP_i}{FPS_i}}{LSf_i} \tag{18}$$

Where CRP_i is the carbon reduction potential of alternative i, FAP_i is the feedstock availability potential of alternative i, FPS_i is the feedstock needed per Mt SAF for alternative i, and LSf_i is the life cycle emissions factor.

Cumulative production: The next step is to calculate the cumulative production per SAF alternative. This will be done using the following formula:

$$CP_{i,t} = \sum_{i=0}^{\infty} P_{i,t} \qquad \forall t \in [2020, 2030] \tag{19}$$

Where $CP_{i,t}$ is the cumulative production of SAF alternative i in year t, and $P_{i,t}$ is the production of an individual producer. The output of this model component is $CP_{i,t}$.

Price development: Learning and scaling effects according to the experience theory can assure lower prices with increased production. The following formula is used, based on the output $CP_{i,t}$ of the previous model component:

$$C_{i,t} = C_{i,t-1} * PR_i^{\log_2 \frac{CP_{i,t}}{CP_{i,t-1}}} \tag{20}$$

Where $C_{i,t}$ is the cost of SAF alternative i in year t, PR_i is the technology-specific process ratio, and $CP_{i,t}$ is the cumulative production of SAF alternative i in year t. The MSP in year $t = 2020$ is $C_{i,2020}$. This model component will lead to the expected cost $C_{i,t}$ as output.

Quantities needed: In this model component, output from ”carbon reduction scenarios” is used. With these data, the expected required fuel quantity can be determined.

$$FQ_{i,t,s} = \frac{EL_t - EG_{t,s}}{ER_i} \tag{21}$$

Where $FQ_{i,t,s}$ is the Fuel Quantity needed for fuel alternative i in year t and scenario s, EL_t is the Emissions Level (after the technological and operational improvements) in year t, $EG_{t,s}$ is the Emission Goal in year t and scenario s, and ER_i is the Emissions Reduction factor of fuel alternative i.

Cost NPV: In the previous two model components, the fuel price and fuel quantity have been specified. This output can be used as input in this component, where the total costs are calculated. The following formula is used:

$$TC_{i,t,s} = FQ_{i,t,s} * (C_{i,t} - C_{CAF}) \tag{22}$$

Where TCi, t, s is the total cost for alternative i, year t and scenario s, $FQ_{i,t,s}$ is the fuel quantity, $C_{i,t}$ is the cost of alternative i in year t, and C_{CAF} is the cost for conventional aviation fuel (fossil fuel).

The fuel costs per year are then summed over the years, taking into account a 10% discount rate to represent a Net Present Value. The following formula is used to calculate NPV:

$$NPV_{i,s} = \sum_{t=2020}^{2050} \frac{TC_{i,t,s}}{(1+i)^t} \tag{23}$$

Where $NPV_{i,s}$ is the Net Present Value for SAF alternative i in scenario s, TCi, t, s is the total cost for alternative i, year t and scenario s, and i is the discount rate or the return that could be earned in alternative investments (set at 10%).

APPENDIX B - SUPPLEMENTARY TABLES

TABLE II: The minimum selling price of SAF according to various sources (USD/t)

Sustainable Aviation Fuel	[60]	[49]	[61]	[45]	[62]	[63]	[64]	[48]	[50]	[65]	[66]	Weighted avg MSP
ATJ-SPK Agricultural residues	3342.21	1810.46	3384.80	2330.23	2500.00		3611.19		1514.20	2678.66	1512.57	2442.06
ATJ-SPK Corn grain	2210.39	1484.49		2077.23	2150.00		2512.78	2321.62		1841.47		2018.41
ATJ-SPK Forestry residues	3342.21	1810.46	2488.83	2396.80	2500.00		3611.19			2678.66	3482.43	2744.26
ATJ-SPK Miscanthus	3342.21	1810.46		2396.80	3250.00		3686.42			2678.66		2800.63
ATJ-SPK Sugarcane	1957.39	1484.49		2077.23	1900.00		2482.69	2075.39		2063.07		1983.75
ATJ-SPK Switchgrass	3342.21	1810.46		3062.58	3250.00		3686.42	3060.32		2678.66		2891.97
FT-SPK Agricultural residues	2000.00	1428.84	2591.32	1184.21	1050.00		2676.32			2398.40		1896.05
FT-SPK Forestry residues	2000.00	1428.84	1843.82	1552.63	1500.00		2676.32			2398.40		1949.95
FT-SPK Miscanthus	2000.00	1428.84		2578.95			2780.39			2398.40		2199.65
FT-SPK Municipal solid waste	1513.16				1550.00		1992.37					1729.06
FT-SPK Poplar	2000.00	1428.84		1552.63	1500.00		2780.39			2398.40	2155.09	1992.66
FT-SPK Switchgrass	2000.00	1428.84		1447.37	1500.00		2780.39			2398.40		1963.36
HEFA-SPK Corn oil				1375.17	1450.00					1250.32		1343.04
HEFA-SPK Palm fatty acid distillate				1375.17	1450.00		1478.50			1250.32		1383.68
HEFA-SPK Palm oil - closed pond		1528.35		1001.34	750.00		1508.68					1274.09
HEFA-SPK Palm oil - open pond		1528.35		1001.34	750.00		1508.68					1274.09
HEFA-SPK Rapeseed oil				1068.09	1150.00	1415.22				1102.19	917.02	1150.57
HEFA-SPK Soybean oil	1588.79	1612.52		1448.60	1450.00		1644.46			1447.83	1551.88	1542.55
HEFA-SPK Tallow	1415.22	1528.35		1535.38	1480.00					1250.32		1436.91
HEFA-SPK Used Cooking Oil	1214.95	1258.12	1501.77	1295.06	1300.00		1327.64			1250.32		1288.43
HFS-SIP Sugar beet			6045.50				5451.75			2373.58	2582.13	3928.79
HFS-SIP Sugarcane			6045.50				5451.75			2373.58	2582.13	3928.79

TABLE III: Governmental mandates to blend SAF

Departure country	Fuel share	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2045	2050
Finland	0.7%											30.0%	30.0%	30.0%
France	2.5%			1.0%	1.0%	1.0%	2.0%	2.0%	2.0%	2.0%	2.0%	5.0%	5.0%	50.0%
Germany	8.7%						0.5%	0.5%	0.5%	1.0%	1.0%	2.0%	2.0%	2.0%
Netherlands	7.1%											14.0%	14.0%	100.0%
Norway	0.2%	0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	8.0%	12.0%	17.0%	23.0%	30.0%	30.0%	30.0%
Spain	15.1%						2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Sweden	2.3%		1.0%	2.0%	3.0%	4.0%	5.0%	8.0%	12.0%	17.0%	23.0%	30.0%	100.0%	100.0%
United States	1.2%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Total	37.6%	0.1%	0.1%	0.1%	0.2%	0.2%	0.6%	0.6%	0.7%	0.9%	1.1%	2.6%	4.2%	11.4%

TABLE IV: A list of CORSIA eligible fuels. LCA values retrieved from ICAO [51].

Conversion process	Fuel feedstock	Bearing	Core LCA value	iLUC LCA value	LSf (gCO2e /MJ)	Generation	ER	LSf (kgCO2e /kg fuel)
ATJ-SPK	Agricultural residues	Lignocellulosic	29.3	0	29.3	2G	2.120	1.04
ATJ-SPK	Corn grain	Lignocellulosic	55.8	22.1	77.9	1G	0.394	2.77
ATJ-SPK	Forestry residues	Lignocellulosic	23.8	0	23.8	2G	2.315	0.85
ATJ-SPK	Miscanthus	Lignocellulosic	43.4	-31	12.4	2G	2.720	0.44
ATJ-SPK	Sugarcane	Sugar/starch	24	7.3	31.3	1G	2.049	1.11
ATJ-SPK	Switchgrass	Lignocellulosic	43.4	-14.5	28.9	2G	2.134	1.03
FT-SPK	Agricultural residues	Lignocellulosic	7.7	0	7.7	2G	2.887	0.27
FT-SPK	Forestry residues	Lignocellulosic	8.3	0	8.3	2G	2.865	0.29
FT-SPK	Miscanthus	Lignocellulosic	10.4	-22	-11.6	2G	3.572	-0.41
FT-SPK	Municipal solid waste	Lignocellulosic	14.8	0	14.8	2G	2.635	0.53
FT-SPK	Poplar	Lignocellulosic	12.2	-5.2	7	2G	2.911	0.25
FT-SPK	Switchgrass	Lignocellulosic	10.4	-3.8	6.6	2G	2.926	0.23
HEFA-SPK	Corn oil	Oil	17.2	0	17.2	2G	2.549	0.61
HEFA-SPK	Palm fatty acid distillate	Oil	20.7	0	20.7	2G	2.425	0.73
HEFA-SPK	Palm oil - closed pond	Oil	37.4	39.1	76.5	1G	0.444	2.72
HEFA-SPK	Palm oil - open pond	Oil	60	39.1	99.1	1G	-0.359	3.52
HEFA-SPK	Rapeseed oil	Oil	47.4	24.1	71.5	1G	0.621	2.54
HEFA-SPK	Soybean oil	Oil	40.4	24.5	64.9	1G	0.856	2.30
HEFA-SPK	Tallow	Oil	22.5	0	22.5	2G	2.361	0.80
HEFA-SPK	Used Cooking Oil	Oil	13.9	0	13.9	2G	2.666	0.49
HFS-SIP	Sugar beet	Sugar/starch	32.4	20.2	52.6	1G	1.292	1.87
HFS-SIP	Sugarcane	Sugar/starch	32.8	11.3	44.1	1G	1.594	1.57

TABLE V: Overview of data validation

Data components	Reliability of sources	Usability of data	Comments
COVID-19 recovery year	No papers, only news articles	Good	Used many sources to conclude with a reliable estimate
TUI Demand data	Reliable, analysis with company data	Very good	Data verified by third party
TUI CO_2 data	Reliable, analysis with company data	Very good	Data verified by third party
Compound Annual Growth Rates	Reliable source by reputation	Good	ICAO is a respected UN institution
Efficiency improvement percentages	Seems reliable, but different data found	Good	Minimums chosen to prevent ”over-budgeting” of carbon reduction
SAF governmental quota	Hard to find data	Fair	Many governmental intentions, this list will extend over the years
Fossil fuel price	Reliable source with 30 year price development	Good	Historical prices don’t necessarily estimate future prices (until 2050)
Market-based Measure costs	Reliable source by reputation	Good	Costs can change in the future
SAF characteristics	Reliable source by reputation	Good	Characteristics must be used within CORSIA carbon reporting
SAF minimum selling prices	Many sources, but different outcomes	Fair	Used a weighted average with many different sources (sort of ”wisdom of the crowd”)
SAF production potential	Reliable sources, but hard to find data	Fair	Used different sources for different SAFs, methodologies of sources may differ
SAF production quantities per year	No papers, only news articles and producer websites	Poor	Producers may keep their production targets confidential, overview may not be complete
Process ratio (PR_i)	Reliable source	Fair	Generic numbers (no SAF) in sources, maximums chosen to prevent ”over-budgeting” of price reduction

B

UN Sustainable Development Goals

Goal 7 Targets: Affordable and Clean Energy [123]

- *By 2030, ensure universal access to affordable, reliable and modern energy services*
- *By 2030, increase substantially the share of renewable energy in the global energy mix*
- *By 2030, double the global rate of improvement in energy efficiency*
- *By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology*
- *By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and landlocked developing countries, in accordance with their respective programmes of support*

Goal 13 Targets: Climate Action [123]

- *Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries*
- *Integrate climate change measures into national policies, strategies and planning*
- *Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning*
- *Implement the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible*

- *Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States, including focusing on women, youth and local and marginalized communities*

**Acknowledging that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change.*

C

Carbon reduction plans of other airlines

Table C.1: Major airlines' carbon reduction goals

Airline	Medium term (2030)	Long term (2050)
Aeromexico		
Air China		
Air France-KLM	15% improvement in net $CO_2$2005-2030, and 50% reduction per RPK	50% improvement in net $CO_2$2005-2050
Air New Zealand		50% improvement in net $CO_2$2005-2050
Alaska Airlines		
American Airlines		Net zero emissions
ANA Group	20% improvement per RPK 2006-2021	
Avianca		50% improvement in net $CO_2$2005-2050
Cargolux		
Cathay Pacific		Net zero emissions
China Eastern Airlines		
China Southern Airlines		
Delta Air Lines		50% improvement in net $CO_2$2005-2050
easyJet	100% carbon offsetting since 2020	
Emirates		
Etihad	50% improvement in net $CO_2$2019-2035	Net zero emissions
FedEx	30% SAF	
Finnair		Net zero emissions
International Airlines Group	20% improvement in net $CO_2$2020-2030	Net zero emissions (30% SAF)
Japan Airlines		Net zero emissions
Jet Blue		50% improvement in net $CO_2$2005-2050
Latam Airlines Group		50% improvement in net $CO_2$2005-2050
Lufthansa Group		
Norwegian	45% improvement per RPK 2010-2030	
Qantas		Net zero emissions
Qatar Airways		Net zero emissions
Ryanair	Below 60 grams CO_2per RPK	50% improvement in net $CO_2$2005-2050
SAS	25% improvement in net $CO_2$2005-2030 17% SAF (equivalent to domestic flights)	More than 50% improvement in net $CO_2$2005-2050
Singapore Airlines	45% improvement per RPK 2010-2030	Net zero emissions
Southwest Airlines		
United Airlines		50% improvement in net $CO_2$2005-2050
Virgin Atlantic		50% improvement in net $CO_2$2005-2050
Virgin Australia		50% improvement in net $CO_2$2005-2050

Table C.2: Airline SAF offtaking agreements

Airline	SAF producer	Feedstock	Process	Offtake location	CAF consumption (Mt/yr)	SAF consumption (Mt/yr)	Percentage	Start of offtake	Length of offtake (years)	Source
Air France-KLM	SkyNRG	UCO	HEFA-SPK	Netherlands	8.961	0.075	0.84%	2022		Air France-KLM [2]
Alaska Airlines	Neste	UCO	HEFA-SPK	San Francisco. USA	8.249					Alaska Airlines [5]
ANA Group	LanzaTech	MSW	FT-SPK	USA. Japan	3.617					ANA Group [7]
Cathay Pacific	Fulcrum	MSW	FT-SPK		5.823	0.114	1.96%	2020	10 years	Cathay Pacific Airways Limited [20]
Delta Air Lines	Gevo	Sugar	ATJ-SPK	USA	13.135	0.030	0.23%	2022		Delta Air Lines [26]
FedEx	RedRock	FR	FT-SPK	Bay Area. California. USA	3.996	0.009	0.23%	2020	7 years	FedEx [36]
International Airlines Group	AltAlto (Velocys)	MSW	FT-SPK	United Kingdom	9.642	0.032	0.33%	2024	20 years	International Airlines Group [60]
Japan Airlines	Fulcrum	MSW	FT-SPK	Japan	2.953			2018		Japan Airlines [64]
Jet Blue	SG Preston	NFPO	HEFA-SPK	New York. USA	2.645	0.100	3.78%	2019	10 years	Jet Blue [65]
Lufthansa Group	Gevo	Sugar	ATJ-SPK		10.254	0.024	0.23%		5 years	Lufthansa Group [78]
Qantas	World Energy (AltAir Fuels) / Agrisoma	Carinata	HEFA-SPK	Australia	3.797	0.160	4.21%	2020		Qantas [98]
SAS	World Energy (AltAir Fuels)	AR	HEFA-SPK	Sweden. Norway	1.337	0.000	0.03%	2018		SAS [100]
Singapore Airlines	Neste	UCO	HEFA-SPK	Stockholm. Sweden	5.159			2020		Singapore Airlines [108]
Southwest Airlines	RedRock	FR	FT-SPK	Bay Area. California. USA	6.483	0.009	0.14%	2020		Southwest Airlines [112]
United Airlines	Fulcrum	MSW	FT-SPK	USA	10.432	0.274	2.63%	2020	10 years	United Airlines [122]
Virgin Atlantic	LanzaTech	MSW	ATJ-SPK	United Kingdom	1.301			2021		Virgin Atlantic [128]
Virgin Australia	Gevo	Sugar	ATJ-SPK	Brisbane. Australia	1.240			2018	1 year	Virgin Australia [129]

D

Sensitivity Analysis

A sensitivity analysis is needed to determine which variables or parameters have the largest impact on the results of the model. This is especially important for future users, because changes in parameters could change the outcome of the model greatly. The ”One-at-a-Time” method is used to determine local sensitivities of the variables. That means that every variable will be changed significantly each time, and the results from the change are noted. This will be repeated until all variables are changed and all results are noted.

The NPV is used as the outcome of the model. All variables are changed by 50% in both directions (decrease and increase) and the percentage difference in NPV results are noted. Some variables (such as years) could not be done using the 50% method, therefore +/- 1 year is used. This can be seen in Table D.1. For the compound annual growth rates, weighted average MSP, and the process ratio, different values were used for different markets or fuels. Therefore, separate tables are made to distinct the exact input in this analysis, as can be seen in Table D.2 and Table D.3.

In the following figures, the results with the percentage changes can be found. A conclusion of this analysis can be found in section 6.4.

Table D.1: General variables in the model for sensitivity analysis

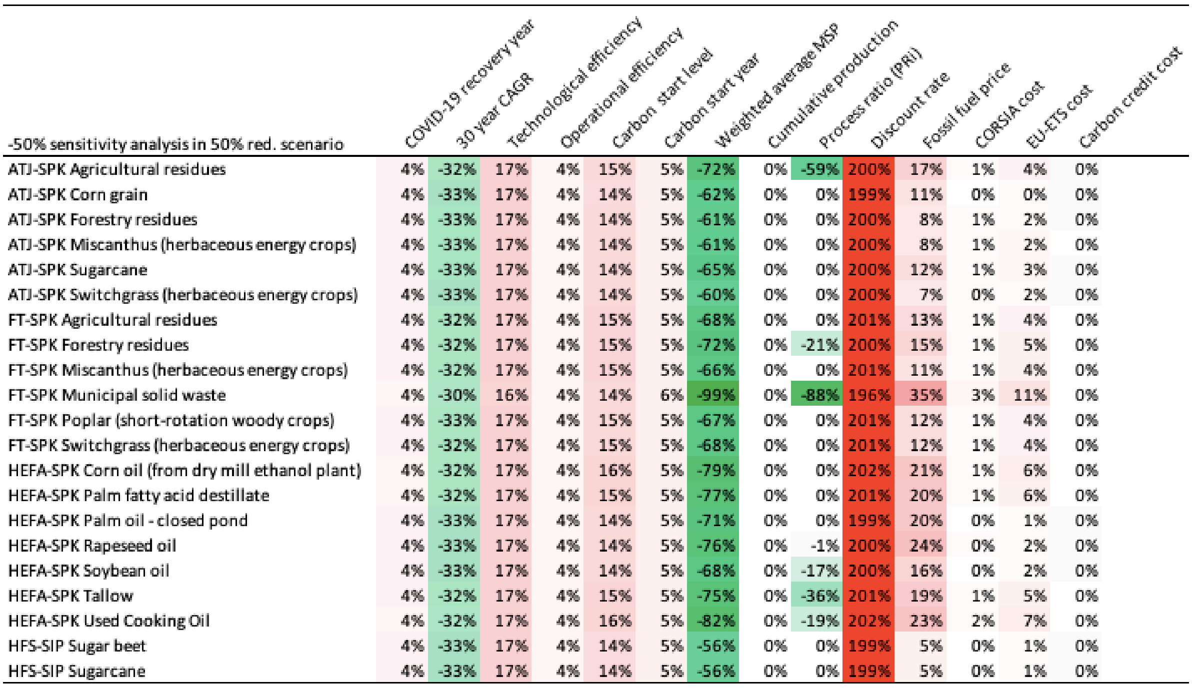
General variables	-50%	Default	+50%
COVID-19 recovery year	2022	2023	2024
Technological efficiency improvement	0.5%	1%	1.5%
Operational efficiency improvement	3%	6%	9%
Carbon start level	0.5%	1%	1.5%
Carbon start year	2022	2023	2024
Discount rate	5%	10%	15%
Fossil fuel price	181.17	362.33	543.50
CORSIA cost	7.50	15.00	22.50
EU-ETS cost	25.00	50.00	75.00
Carbon credit cost	5.00	10.00	15.00

Table D.2: Compound Annual Growth Rates (CAGR) in the model for sensitivity analysis

Compound Annual Growth Rates	-50%	Default	+50%
Central America / Caribbean	1.9%	3.8%	5.7%
Central and South-West Asia	2.6%	5.1%	7.7%
Intra Europe	1.3%	2.6%	3.9%
Middle East	2.0%	4.0%	6.0%
North Africa	2.1%	4.1%	6.2%
North America	1.3%	2.6%	3.9%
Pacific South-East Asia	2.2%	4.4%	6.6%
South America	2.1%	4.1%	6.2%
Sub Saharan Africa	1.4%	2.8%	4.2%

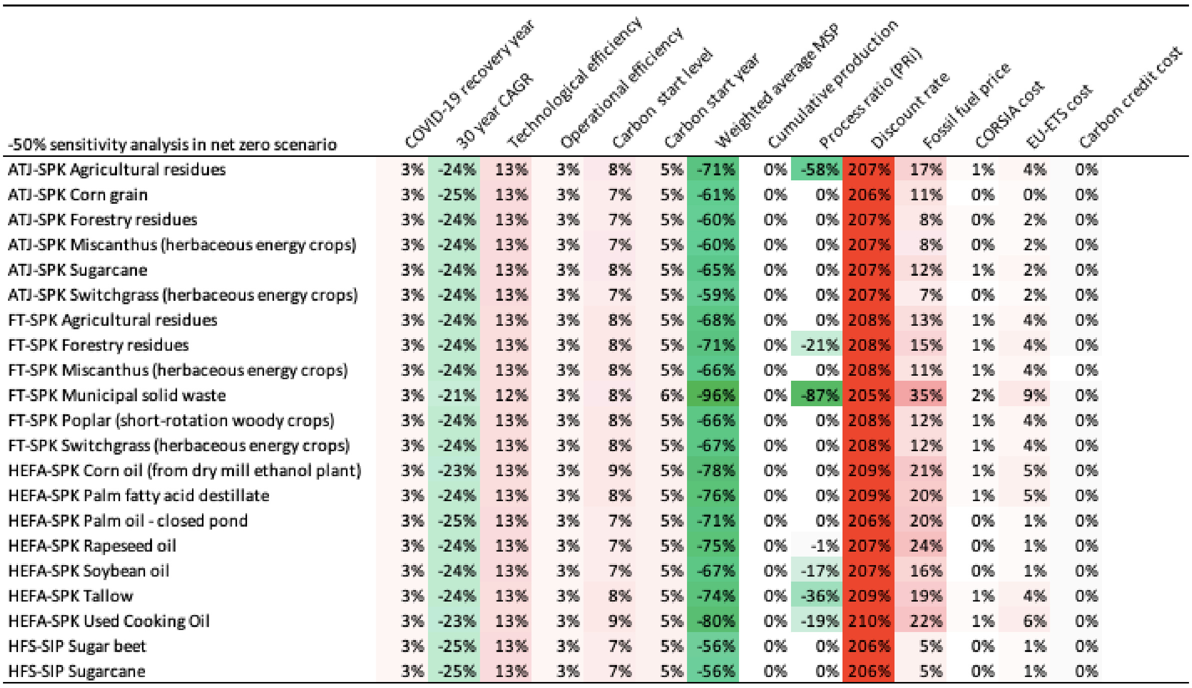
Table D.3: Weighted average MSP and Process Ratio in the model for sensitivity analysis

	Weighted average MSP			Process ratio (PR_i)		
Sustainable Aviation Fuel	-50%	Default	+50%	-0.10	Default	+0.10
ATJ-SPK Agricultural residues	1221.03	2442.06	3663.09	0.8	0.9	1
ATJ-SPK Corn grain	1009.20	2018.41	3027.61	0.8	0.9	1
ATJ-SPK Forestry residues	1372.13	2744.26	4116.38	0.8	0.9	1
ATJ-SPK Miscanthus (herbaceous energy crops)	1400.32	2800.63	4200.95	0.8	0.9	1
ATJ-SPK Sugarcane	991.87	1983.75	2975.62	0.8	0.9	1
ATJ-SPK Switchgrass (herbaceous energy crops)	1445.99	2891.97	4337.96	0.8	0.9	1
FT-SPK Agricultural residues	948.03	1896.05	2844.08	0.8	0.9	1
FT-SPK Forestry residues	974.98	1949.95	2924.93	0.8	0.9	1
FT-SPK Miscanthus (herbaceous energy crops)	1099.82	2199.65	3299.47	0.8	0.9	1
FT-SPK Municipal solid waste	864.53	1729.06	2593.59	0.8	0.9	1
FT-SPK Poplar (short-rotation woody crops)	996.33	1992.66	2988.99	0.8	0.9	1
FT-SPK Switchgrass (herbaceous energy crops)	981.68	1963.36	2945.04	0.8	0.9	1
HEFA-SPK Corn oil (from dry mill ethanol plant)	671.52	1343.04	2014.56	0.9	1	1
HEFA-SPK Palm fatty acid destillate	691.84	1383.68	2075.52	0.9	1	1
HEFA-SPK Palm oil - closed pond	637.04	1274.09	1911.13	0.9	1	1
HEFA-SPK Palm oil - open pond	637.04	1274.09	1911.13	0.9	1	1
HEFA-SPK Rapeseed oil	575.29	1150.57	1725.86	0.9	1	1
HEFA-SPK Soybean oil	771.27	1542.55	2313.82	0.9	1	1
HEFA-SPK Tallow	718.46	1436.91	2155.37	0.9	1	1
HEFA-SPK Used Cooking Oil	644.21	1288.43	1932.64	0.9	1	1
HFS-SIP Sugar beet	1964.39	3928.79	5893.18	0.8	0.9	1
HFS-SIP Sugarcane	1964.39	3928.79	5893.18	0.8	0.9	1



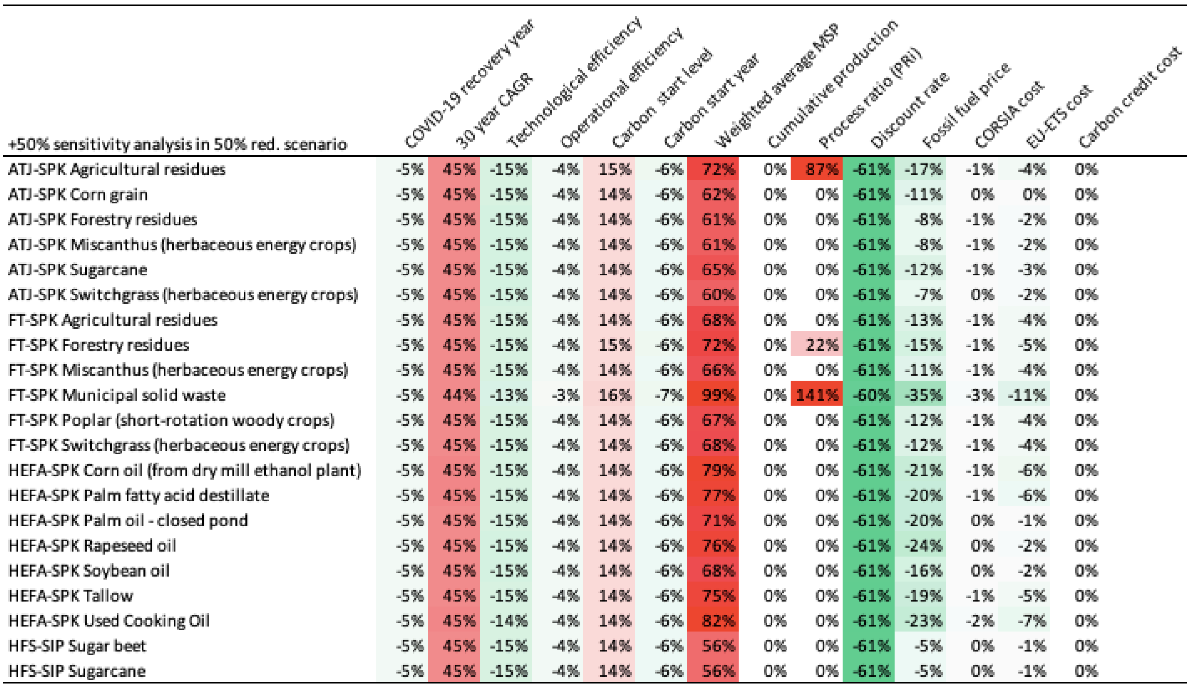
-50% sensitivity analysis in 50% red. scenario	COVID-19 recovery year	30 year CAGR	Technological efficiency	Operational efficiency	Carbon start level	Carbon start year	Weighted average MSP	Cumulative production	Process ratio (PRI)	Discount rate	Fossil fuel price	CORSIA cost	EU-ETS cost	Carbon credit cost
ATJ-SPK Agricultural residues	4%	-32%	17%	4%	15%	5%	-72%	0%	-59%	200%	17%	1%	4%	0%
ATJ-SPK Corn grain	4%	-33%	17%	4%	14%	5%	-62%	0%	0%	199%	11%	0%	0%	0%
ATJ-SPK Forestry residues	4%	-33%	17%	4%	14%	5%	-61%	0%	0%	200%	8%	1%	2%	0%
ATJ-SPK Miscanthus (herbaceous energy crops)	4%	-33%	17%	4%	14%	5%	-61%	0%	0%	200%	8%	1%	2%	0%
ATJ-SPK Sugarcane	4%	-33%	17%	4%	14%	5%	-65%	0%	0%	200%	12%	1%	3%	0%
ATJ-SPK Switchgrass (herbaceous energy crops)	4%	-33%	17%	4%	14%	5%	-60%	0%	0%	200%	7%	0%	2%	0%
FT-SPK Agricultural residues	4%	-32%	17%	4%	15%	5%	-68%	0%	0%	201%	13%	1%	4%	0%
FT-SPK Forestry residues	4%	-32%	17%	4%	15%	5%	-72%	0%	-21%	200%	15%	1%	5%	0%
FT-SPK Miscanthus (herbaceous energy crops)	4%	-32%	17%	4%	15%	5%	-66%	0%	0%	201%	11%	1%	4%	0%
FT-SPK Municipal solid waste	4%	-30%	16%	4%	14%	6%	-99%	0%	-88%	196%	35%	3%	11%	0%
FT-SPK Poplar (short-rotation woody crops)	4%	-33%	17%	4%	15%	5%	-67%	0%	0%	201%	12%	1%	4%	0%
FT-SPK Switchgrass (herbaceous energy crops)	4%	-32%	17%	4%	15%	5%	-68%	0%	0%	201%	12%	1%	4%	0%
HEFA-SPK Corn oil (from dry mill ethanol plant)	4%	-32%	17%	4%	16%	5%	-79%	0%	0%	202%	21%	1%	6%	0%
HEFA-SPK Palm fatty acid destillate	4%	-32%	17%	4%	15%	5%	-77%	0%	0%	201%	20%	1%	6%	0%
HEFA-SPK Palm oil - closed pond	4%	-33%	17%	4%	14%	5%	-71%	0%	0%	199%	20%	0%	1%	0%
HEFA-SPK Rapeseed oil	4%	-33%	17%	4%	14%	5%	-76%	0%	-1%	200%	24%	0%	2%	0%
HEFA-SPK Soybean oil	4%	-33%	17%	4%	14%	5%	-68%	0%	-17%	200%	16%	0%	2%	0%
HEFA-SPK Tallow	4%	-32%	17%	4%	15%	5%	-75%	0%	-36%	201%	19%	1%	5%	0%
HEFA-SPK Used Cooking Oil	4%	-32%	17%	4%	16%	5%	-82%	0%	-19%	202%	23%	2%	7%	0%
HFS-SIP Sugar beet	4%	-33%	17%	4%	14%	5%	-56%	0%	0%	199%	5%	0%	1%	0%
HFS-SIP Sugarcane	4%	-33%	17%	4%	14%	5%	-56%	0%	0%	199%	5%	0%	1%	0%

Figure D.1: -50% Sensitivity analysis in 50% reduction scenario



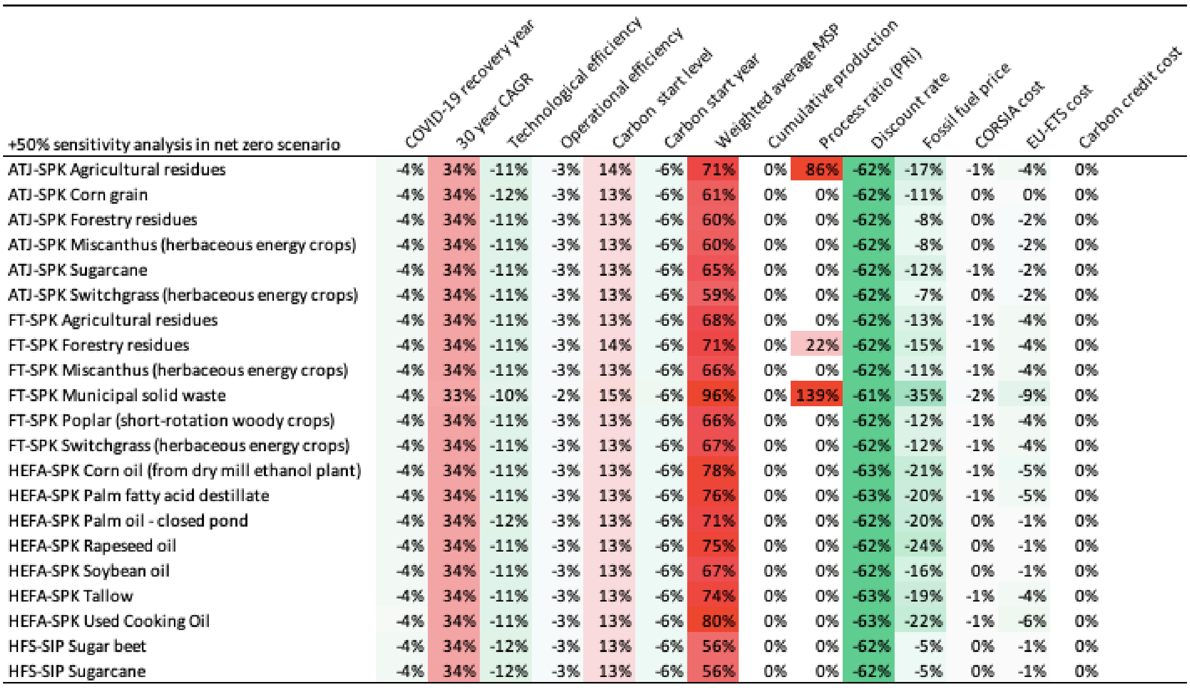
-50% sensitivity analysis in net zero scenario	COVID-19 recovery year	30 year CAGR	Technological efficiency	Operational efficiency	Carbon start level	Carbon start year	Weighted average MSP	Cumulative production	Process ratio (PRI)	Discount rate	Fossil fuel price	CORSIA cost	EU-ETS cost	Carbon credit cost
ATJ-SPK Agricultural residues	3%	-24%	13%	3%	8%	5%	-71%	0%	-58%	207%	17%	1%	4%	0%
ATJ-SPK Corn grain	3%	-25%	13%	3%	7%	5%	-61%	0%	0%	206%	11%	0%	0%	0%
ATJ-SPK Forestry residues	3%	-24%	13%	3%	7%	5%	-60%	0%	0%	207%	8%	0%	2%	0%
ATJ-SPK Miscanthus (herbaceous energy crops)	3%	-24%	13%	3%	7%	5%	-60%	0%	0%	207%	8%	0%	2%	0%
ATJ-SPK Sugarcane	3%	-24%	13%	3%	8%	5%	-65%	0%	0%	207%	12%	1%	2%	0%
ATJ-SPK Switchgrass (herbaceous energy crops)	3%	-24%	13%	3%	7%	5%	-59%	0%	0%	207%	7%	0%	2%	0%
FT-SPK Agricultural residues	3%	-24%	13%	3%	8%	5%	-68%	0%	0%	208%	13%	1%	4%	0%
FT-SPK Forestry residues	3%	-24%	13%	3%	8%	5%	-71%	0%	-21%	208%	15%	1%	4%	0%
FT-SPK Miscanthus (herbaceous energy crops)	3%	-24%	13%	3%	8%	5%	-66%	0%	0%	208%	11%	1%	4%	0%
FT-SPK Municipal solid waste	3%	-21%	12%	3%	8%	6%	-96%	0%	-87%	205%	35%	2%	9%	0%
FT-SPK Poplar (short-rotation woody crops)	3%	-24%	13%	3%	8%	5%	-66%	0%	0%	208%	12%	1%	4%	0%
FT-SPK Switchgrass (herbaceous energy crops)	3%	-24%	13%	3%	8%	5%	-67%	0%	0%	208%	12%	1%	4%	0%
HEFA-SPK Corn oil (from dry mill ethanol plant)	3%	-23%	13%	3%	9%	5%	-78%	0%	0%	209%	21%	1%	5%	0%
HEFA-SPK Palm fatty acid destillate	3%	-24%	13%	3%	8%	5%	-76%	0%	0%	209%	20%	1%	5%	0%
HEFA-SPK Palm oil - closed pond	3%	-25%	13%	3%	7%	5%	-71%	0%	0%	206%	20%	0%	1%	0%
HEFA-SPK Rapeseed oil	3%	-24%	13%	3%	7%	5%	-75%	0%	-1%	207%	24%	0%	1%	0%
HEFA-SPK Soybean oil	3%	-24%	13%	3%	7%	5%	-67%	0%	-17%	207%	16%	0%	1%	0%
HEFA-SPK Tallow	3%	-24%	13%	3%	8%	5%	-74%	0%	-36%	209%	19%	1%	4%	0%
HEFA-SPK Used Cooking Oil	3%	-23%	13%	3%	9%	5%	-80%	0%	-19%	210%	22%	1%	6%	0%
HFS-SIP Sugar beet	3%	-25%	13%	3%	7%	5%	-56%	0%	0%	206%	5%	0%	1%	0%
HFS-SIP Sugarcane	3%	-25%	13%	3%	7%	5%	-56%	0%	0%	206%	5%	0%	1%	0%

Figure D.2: -50% Sensitivity analysis in net zero scenario



+50% sensitivity analysis in 50% red. scenario	COVID-19 recovery year	30 year CAGR	Technological efficiency	Operational efficiency	Carbon start level	Carbon start year	Weighted average MSP	Cumulative production	Process ratio (PRI)	Discount rate	Fossil fuel price	CORSIA cost	EU-ETS cost	Carbon credit cost
ATJ-SPK Agricultural residues	-5%	45%	-15%	-4%	15%	-6%	72%	0%	87%	-61%	-17%	-1%	-4%	0%
ATJ-SPK Corn grain	-5%	45%	-15%	-4%	14%	-6%	62%	0%	0%	-61%	-11%	0%	0%	0%
ATJ-SPK Forestry residues	-5%	45%	-15%	-4%	14%	-6%	61%	0%	0%	-61%	-8%	-1%	-2%	0%
ATJ-SPK Miscanthus (herbaceous energy crops)	-5%	45%	-15%	-4%	14%	-6%	61%	0%	0%	-61%	-8%	-1%	-2%	0%
ATJ-SPK Sugarcane	-5%	45%	-15%	-4%	14%	-6%	65%	0%	0%	-61%	-12%	-1%	-3%	0%
ATJ-SPK Switchgrass (herbaceous energy crops)	-5%	45%	-15%	-4%	14%	-6%	60%	0%	0%	-61%	-7%	0%	-2%	0%
FT-SPK Agricultural residues	-5%	45%	-15%	-4%	14%	-6%	68%	0%	0%	-61%	-13%	-1%	-4%	0%
FT-SPK Forestry residues	-5%	45%	-15%	-4%	15%	-6%	72%	0%	22%	-61%	-15%	-1%	-5%	0%
FT-SPK Miscanthus (herbaceous energy crops)	-5%	45%	-15%	-4%	14%	-6%	66%	0%	0%	-61%	-11%	-1%	-4%	0%
FT-SPK Municipal solid waste	-5%	44%	-13%	-3%	16%	-7%	99%	0%	141%	-60%	-35%	-3%	-11%	0%
FT-SPK Poplar (short-rotation woody crops)	-5%	45%	-15%	-4%	14%	-6%	67%	0%	0%	-61%	-12%	-1%	-4%	0%
FT-SPK Switchgrass (herbaceous energy crops)	-5%	45%	-15%	-4%	14%	-6%	68%	0%	0%	-61%	-12%	-1%	-4%	0%
HEFA-SPK Corn oil (from dry mill ethanol plant)	-5%	45%	-15%	-4%	14%	-6%	79%	0%	0%	-61%	-21%	-1%	-6%	0%
HEFA-SPK Palm fatty acid destillate	-5%	45%	-15%	-4%	14%	-6%	77%	0%	0%	-61%	-20%	-1%	-6%	0%
HEFA-SPK Palm oil - closed pond	-5%	45%	-15%	-4%	14%	-6%	71%	0%	0%	-61%	-20%	0%	-1%	0%
HEFA-SPK Rapeseed oil	-5%	45%	-15%	-4%	14%	-6%	76%	0%	0%	-61%	-24%	0%	-2%	0%
HEFA-SPK Soybean oil	-5%	45%	-15%	-4%	14%	-6%	68%	0%	0%	-61%	-16%	0%	-2%	0%
HEFA-SPK Tallow	-5%	45%	-15%	-4%	14%	-6%	75%	0%	0%	-61%	-19%	-1%	-5%	0%
HEFA-SPK Used Cooking Oil	-5%	45%	-14%	-4%	14%	-6%	82%	0%	0%	-61%	-23%	-2%	-7%	0%
HFS-SIP Sugar beet	-5%	45%	-15%	-4%	14%	-6%	56%	0%	0%	-61%	-5%	0%	-1%	0%
HFS-SIP Sugarcane	-5%	45%	-15%	-4%	14%	-6%	56%	0%	0%	-61%	-5%	0%	-1%	0%

Figure D.3: +50% Sensitivity analysis in 50% reduction scenario



+50% sensitivity analysis in net zero scenario	COVID-19 recovery year	30 year CAGR	Technological efficiency	Operational efficiency	Carbon start level	Carbon start year	Weighted average MSP	Cumulative production	Process ratio (PRI)	Discount rate	Fossil fuel price	CORSIA cost	EU-ETS cost	Carbon credit cost
ATJ-SPK Agricultural residues	-4%	34%	-11%	-3%	14%	-6%	71%	0%	86%	-62%	-17%	-1%	-4%	0%
ATJ-SPK Corn grain	-4%	34%	-12%	-3%	13%	-6%	61%	0%	0%	-62%	-11%	0%	0%	0%
ATJ-SPK Forestry residues	-4%	34%	-11%	-3%	13%	-6%	60%	0%	0%	-62%	-8%	0%	-2%	0%
ATJ-SPK Miscanthus (herbaceous energy crops)	-4%	34%	-11%	-3%	13%	-6%	60%	0%	0%	-62%	-8%	0%	-2%	0%
ATJ-SPK Sugarcane	-4%	34%	-11%	-3%	13%	-6%	65%	0%	0%	-62%	-12%	-1%	-2%	0%
ATJ-SPK Switchgrass (herbaceous energy crops)	-4%	34%	-11%	-3%	13%	-6%	59%	0%	0%	-62%	-7%	0%	-2%	0%
FT-SPK Agricultural residues	-4%	34%	-11%	-3%	13%	-6%	68%	0%	0%	-62%	-13%	-1%	-4%	0%
FT-SPK Forestry residues	-4%	34%	-11%	-3%	14%	-6%	71%	0%	22%	-62%	-15%	-1%	-4%	0%
FT-SPK Miscanthus (herbaceous energy crops)	-4%	34%	-11%	-3%	13%	-6%	66%	0%	0%	-62%	-11%	-1%	-4%	0%
FT-SPK Municipal solid waste	-4%	33%	-10%	-2%	15%	-6%	96%	0%	139%	-61%	-35%	-2%	-9%	0%
FT-SPK Poplar (short-rotation woody crops)	-4%	34%	-11%	-3%	13%	-6%	66%	0%	0%	-62%	-12%	-1%	-4%	0%
FT-SPK Switchgrass (herbaceous energy crops)	-4%	34%	-11%	-3%	13%	-6%	67%	0%	0%	-62%	-12%	-1%	-4%	0%
HEFA-SPK Corn oil (from dry mill ethanol plant)	-4%	34%	-11%	-3%	13%	-6%	78%	0%	0%	-63%	-21%	-1%	-5%	0%
HEFA-SPK Palm fatty acid destillate	-4%	34%	-11%	-3%	13%	-6%	76%	0%	0%	-63%	-20%	-1%	-5%	0%
HEFA-SPK Palm oil - closed pond	-4%	34%	-12%	-3%	13%	-6%	71%	0%	0%	-62%	-20%	0%	-1%	0%
HEFA-SPK Rapeseed oil	-4%	34%	-11%	-3%	13%	-6%	75%	0%	0%	-62%	-24%	0%	-1%	0%
HEFA-SPK Soybean oil	-4%	34%	-11%	-3%	13%	-6%	67%	0%	0%	-62%	-16%	0%	-1%	0%
HEFA-SPK Tallow	-4%	34%	-11%	-3%	13%	-6%	74%	0%	0%	-63%	-19%	-1%	-4%	0%
HEFA-SPK Used Cooking Oil	-4%	34%	-11%	-3%	13%	-6%	80%	0%	0%	-63%	-22%	-1%	-6%	0%
HFS-SIP Sugar beet	-4%	34%	-12%	-3%	13%	-6%	56%	0%	0%	-62%	-5%	0%	-1%	0%
HFS-SIP Sugarcane	-4%	34%	-12%	-3%	13%	-6%	56%	0%	0%	-62%	-5%	0%	-1%	0%

Figure D.4: +50% Sensitivity analysis in net zero scenario