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.

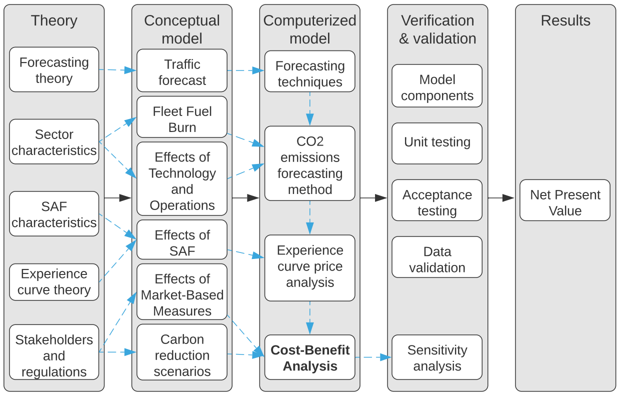

Fig. 1: Research framework

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.

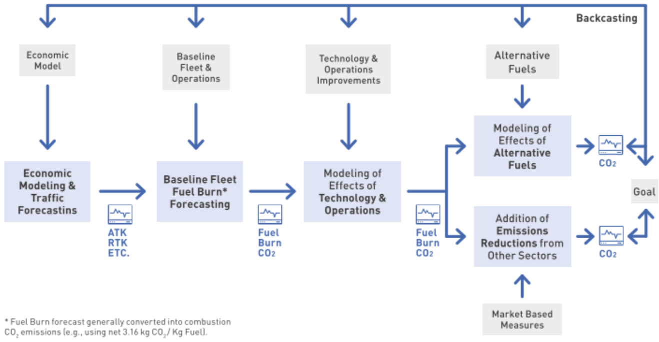

Fig. 2: Method for forecasting CO_2 emissions. Adapted from ATAG [9]

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.

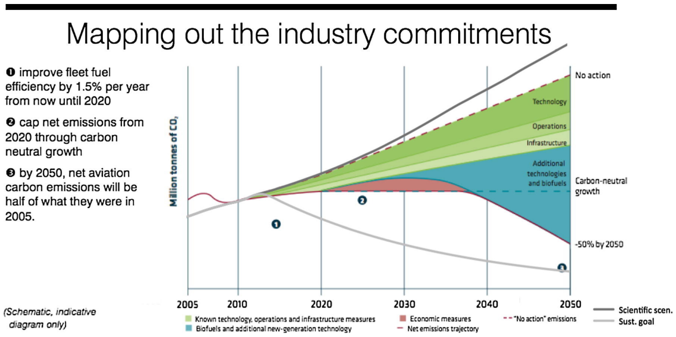

Fig. 3: Long term targets for international aviation CO_2 emissions. Adapted from Peeters et al. [37]

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

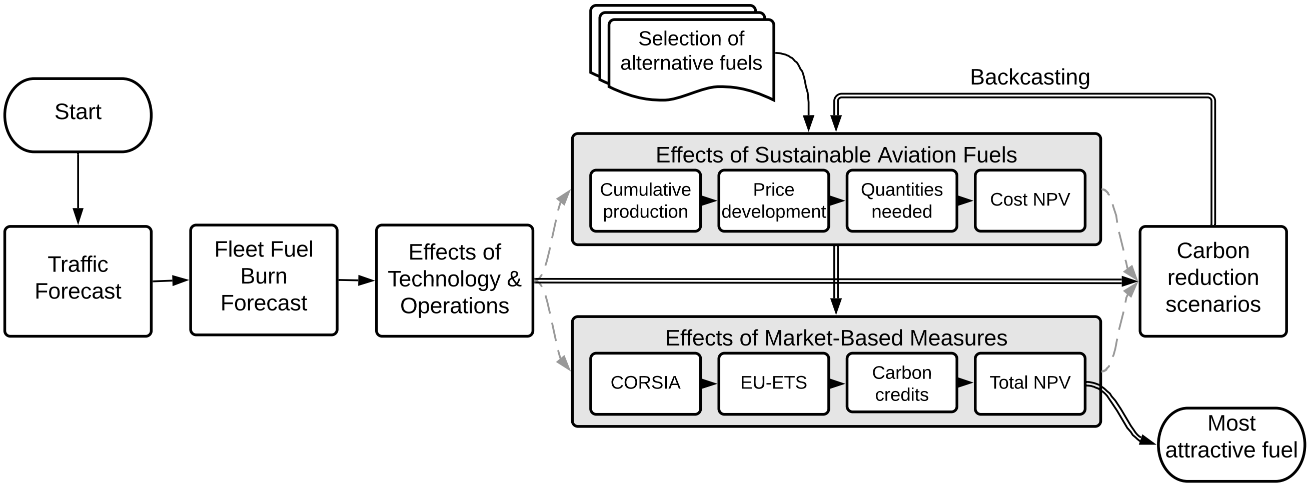

Fig. 4: Conceptual Model. Grey intermittent arrows are not active anymore, replaced by double black arrows.

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.

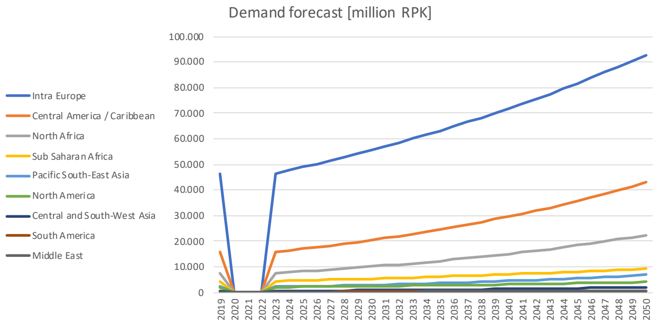

Fig. 5: Demand forecast for TUI Aviation in 2020-2050 in million Revenue Passenger Kilometers

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).

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.

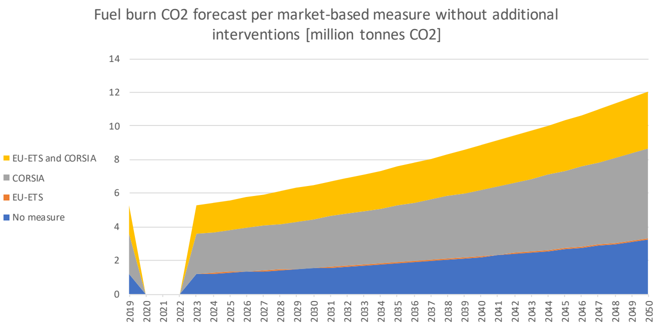

Fig. 6: CO_2 forecast for TUI Aviation in 2020-2050 in million metric tonnes of CO_2 per MBM

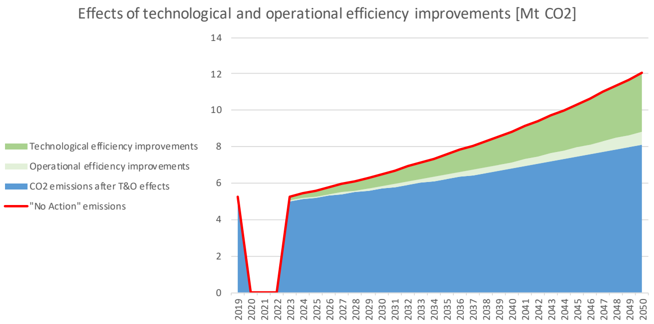

Fig. 7: The effects of technological and operational efficiency improvements on the fuel burn CO_2 forecast of TUI Aviation

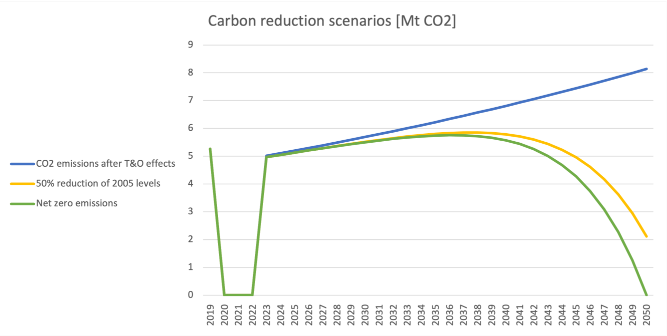

Fig. 8: Scenario forecast for TUI Aviation in 2020-2050

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.

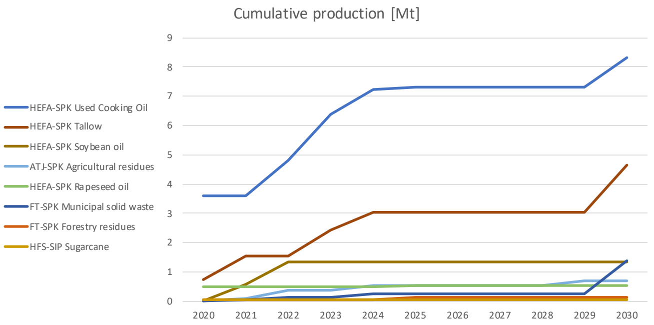

Fig. 9: Cumulative production of fuel alternatives (in Mt), only showing the alternatives with known production quantities and including diesel fuels

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.

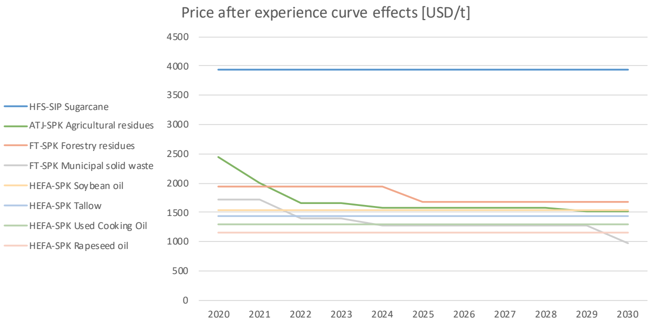

Fig. 10: Cost of fuel alternatives after experience curve effects (in USD/ton)

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.

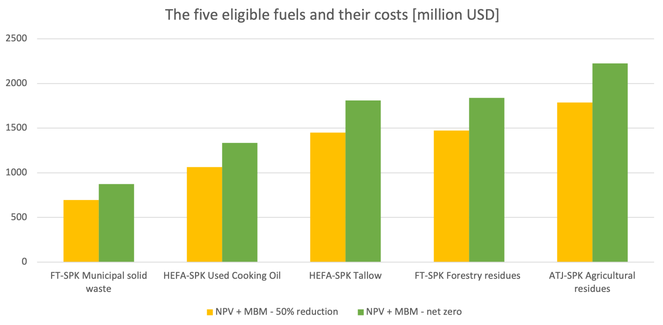

Fig. 11: The resulting fuels that could be implemented in TUI Aviation operations

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).

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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