Sustainable Aviation Fuel in a Scandinavian Context

A Systems Perspective on Sustainable Transitions within the Aviation Industry

Edvin Andreasson

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System Dynamics Group

Department of Geography, Faculty of Social Sciences

University of Bergen, Norway

Supervisor:
Saeed P. langarudi, *Professor in System Dynamics*, University of Bergen

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Abstract

The aviation sector is a major contributor to global carbon emissions, accounting for approximately 2.5% of total global emissions. The main contributor to these emissions is the production and consumption of aviation fuel, hence, transitioning to sustainable aviation fuel (SAF) is a critical step towards reducing the industry's carbon footprint. However, the adoption of SAF presents complex challenges that extend beyond environmental considerations and include industrial as well as business aspects. This paper focuses on the demand for SAF in the Scandinavian aviation industry and explores different pathways for its adoption. A system dynamics model is developed and simulated under varying parameters and scenarios to examine the transition to SAF. The results for each Scandinavian country are presented and discussed, along with potential policies to aid the transition. The overview is that biofuel is the first to be adopted, followed by e-fuel, and lastly hydrogen but the timing is varied with Sweden being the first to start adopting SAFs. The paper then identifies mechanisms that are better targets for intervention and can inform decision-making in the adoption of SAFs in the aviation industry. The study offers insights into the challenges and opportunities of transitioning to SAF and highlights the importance of a coordinated effort involving multiple stakeholders, including airlines, fuel producers, policymakers, and consumers.

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Abbreviations

Abbreviation	*Full Form*	*Definition*
ATJ	Alcohol to Jet	A process of turning alcohol into bio jet fuel
CCS	Carbon Capture Storage	Carbon capture storage is technology that allows for carbon (CO2) to be captured from emissions
CCU	Carbon Capture Utilization	A technology that allows to capture carbon from the atmosphere and then use it other process such as the creation of e-fuel
FT	Fischer Tropsch Method	A process of turning biomass into bio jet fuel
PTL	Power-to-Liquid	A production plan that takes power from renewable sources and turns into liquid chemical such as hydrogen or other fuels
PTX	Power-to-X	A production chain that takes power from the grid in off hours and produces heating, chemicals, hydrogen, and other energy intensive products
RES	Renewable Energy Sources	Energy sources that are renewable
SAF	Sustainable Aviation Fuel	Any jet fuel that comes from sustainable sources and emits low amounts of CO2e
SD	System Dynamics	A methodology focused on conveying feedback mechanism and nonlinearities into a simulation model
TAF	Traditional Aviation Fuel	Jet fuels that are high emission, hydrocarbon based, and currently in use

Chapter 1: Introduction

1.1 Problem

The global climate target of a maximum increase of 1.5 degrees Celsius is becoming increasingly unachievable. The world is simply not doing enough, fast enough to meaningfully reduce the advancement of global warming (IRENA 2021). Yet, all industrial sectors are undergoing some type of transition to combat climate change, be that reduction in CO2 by switching to renewable (carbon neutral) energy sources, shifting materials to more sustainable options, re-thinking supply chains, and relying on technological advancement in all facets of the interconnected businesses (Ydersbond et al. 2020). Many sectors face serious decisions about which path to choose. To complicate matters further, there are multiple pathways under each decision as well. A sector that highlights these obstacles notably is the aviation sector (ATAG 2021).

The aviation sector is a major contributor to global carbon emissions, accounting for approximately 2.5% of total global emissions (Airbus 2020; Ydersbond et al. 2020). The main contributor to these emissions is the production and consumption of aviation fuel (Ydersbond et al. 2020). Therefore, the challenges of transitioning to a more sustainable mode of transport are centred around the fuel share. That is difficult as these challenges are prevalent in the production line. To produce any type of sustainable aviation fuel (SAF) there needs to be adequate renewable energy sources and production (Kristensen 2021). Once the fuel is able to be produced, then, depending on the fuel, new infrastructure, and updated models of aeroplanes also need to be put in place.

The transition within the aviation sector presents a complex problem involving environmental, industrial, and business challenges including the need for new infrastructure, modifications to the fleet, as well as economic and regulatory obstacles. However, as costly, slow, and tedious the transition may be, the urgency of it cannot be understated. It can be argued that the 2.5% of emissions is not a significant share and there are sectors that emit more and thus, should be receiving greater attention. The aviation industry is a particularly difficult sector to transition and thus, any insights from studying the aviation industry can be applied in less "difficult" sectors.

To further complicate the matter of fuel production, the market exists currently within a 'chicken and the egg' misalignment (Andreasen & Sovacool 2014; DNV 2022a; NTRANS 2021). Meaning that the supply side of the market is hesitant to increase production as there are uncertainties of whether demand will be there. The demand side is hesitant as consumers are uncertain whether the demand can be met. Additionally, if the supply side does not start increasing production, the cost of the fuel itself will be too expensive to become viable (Rondinelli et al. 2017).

This places Scandinavia in a unique position where they, due to their dormant renewable potential, can lead the adoption of sustainable aviation fuel. There are quite a few plans in place to develop this potential through Power-to-X (PTX), and Power-to-Liquid (PtL) projects (ENS 2021; Nordic Energy Research 2021; Statkraft 2021). So, the supply side is being developed and, for the purposes of this study, is assumed to be steadily increasing. That means the object of examination is the demand aspect, i.e., the share of aviation fuel being sustainable alternatives. Thus, the research question becomes:

RQ: "What will be the transitional path of demand for sustainable aviation fuel?"

More specifically, the purpose of this thesis is to explore different pathways that will lead to the adoption of SAF in the Scandinavian countries (Denmark, Norway, and Sweden). Specifically, to find insights, unforeseen consequences, and where policies can intervene to aid in the transition. Discovering the inflection points in the transition, from the model and the potential reality, will help provide awareness about mechanisms that are better targets for intervention.

Before discussing the demand aspect of SAF, it is important to highlight the properties and differences between the SAFs as those characteristics are the defining reasons for deciding to use that fuel. A low energy density, high emission fuels for example, would not be beneficial to a transition. Comparing and contrasting the different fuels will inform parameters and, structure, allowing for discussion that could not happen with only the model behaviour, such as externalities or effects on other aspects of a country. Therefore, the following question needs to be discussed:

SRQ1: "What are the properties of the different SAFs and how does that affect the transition?"

Furthermore, to be able to predict demand in response to shocks and interventions, there needs to be an exploration into the factors that drive demand. The decisions and operational process of the executives that decide which fuels to use are essential for understanding the paths to its adoption. This informs the next sub question that requires thought:

SRQ2: "What are the main drivers of demand for SAF in the Scandinavian aviation industry?"

Once the drivers of demand and the properties of each fuel have been realized then the last exploration is to see where the sensitivity of the system lies. There may be a certain driver that would allow for transition to occur more rapidly. This aspects focus is whether there are state or corporate interventions or strategies that can meet the urgency of the transition. The final question is therefore:

SRQ3: "What strategies can be implemented to increase the demand for SAF in the Scandinavian aviation industry?"

The findings of the project indicate that the main challenge of the transition is the price of the SAF, as the companies are inherently economically minded and thus will only transition if the price is within the acceptable range and the transitional costs, such as infrastructure, are deemed worth it to get access to a 'more beneficial' future in terms of environmental gains. There are differences between Norway, Sweden, and Denmark and that stems from geographical, social, and energy production related obstacles. Since SAF is only sustainable if the production and supply line is decarbonized, there needs to be sufficient renewable energy production to sustain consistent and growing SAF production. Thus, any policy to affect the price of either traditional aviation fuel (TAF) and SAF needs to be supply side focused to guarantee sufficient supplies.

The thesis is divided into five chapters that each pertain(s) to a different aspect of the problem, the model, and the discussion. The first chapter initializes the problem formulation by putting it in the larger context of sustainable transitions. It also provides all the necessary background information about the fuels and methodology. The chapter finishes with an overview of the dynamic hypothesis that informs the quantifiable model.

Chapter 2 focuses on the system dynamics model and its robustness. The model is introduced in greater detail than the dynamic hypothesis, along with the assumptions for the parameters. The sensitivity and validation framework conceptualized by Barlas (1996) is then applied on the model to grasp the full simulation range and sensitivity of the simulation space.

Chapter 3 contains the analysis, where the results for each country are presented and discussed. It covers the three countries, and possible policies that can aid in the transition. The behaviour is compared between the countries and the underlying reason for the divergence is discussed in depth.

Chapter 4 is the discussion of results and implications that the thesis indicates. The discussion relates the findings to a larger body of research on energy transitions, rebound effects, and electricity.

Chapter 5 consists of the conclusionary remarks, limitations, and further research. The results and discussion are further elaborated upon and concluded.

1.2 Aviation Industry & its Fuel

Aviation and sustainability are complex topics that range over engineering, economic, and chemistry concepts that, unless one was to study this niche, but increasingly important interdisciplinary field, it can be confusing to understand. This section will go over the required knowledge, terminology, differentiate the fuels, discuss assumptions, the challenges of transitioning, and prior works on the topic. The goal is to convey this information as simply and concisely as can be, as each topic could be a research paper in itself. That being said it is important to keep in mind the scope of this research and that the information presented here is limited to that scope.

1.2.1 What the Fuel?

The overarching types of fuels that this research focuses on is Biofuel, E-fuel, and Hydrogen. These overarching types contain a multitude of different fuels and derivatives as well, depending on feedstocks and type of production (ICAO 2019; Su-Ungkavatin et al. 2023). Most of these pathways are not covered or discussed in the thesis, as that would extend it to unreasonable territory. Thus, the report focuses on the overarching categories and their differences (Su-Ungkavatin et al. 2023).

So far, only the types of sustainable aviation fuels (SAFs) have been talked about, the question of what an SAF is still remains. To put it simply, a sustainable aviation fuel is any fuel that is produced with a greener production line compared to traditional aviation fuel (Agarwal 2012). A greener production line could be the production of Jet A-1 (the most common commercial jet fuel) with renewable energy and green inputs, thus, reducing the overall CO2e emissions, if accounting for carbon capture storage (CCS) or carbon capture utilization (CCU) (Ballal 2023). This would make the fuel produced a synthetic fuel or electro-fuel, shortened for simplicity to e-fuel. Another alternative fuel is bio-produced fuel, referred to as biofuel. It can take any biomass and through various chemical processes can turn those into usable fuel. This section starts by going into details about e-fuel and biofuel before discussing hydrogen as an energy carrier.

E-fuels are traditional jet fuels made with renewable electricity and carbon dioxide (CO_2) which results in a life cycle assessment reduction of CO_2e emissions or, in some cases, negative emissions, as CO_2 is consumed in the production (Ramirez et al. 2020). This is due to theoretically absorbing more CO_2 than it is releasing when burned (Ballal 2023). However, it is important to note that studies on CO_2 emissions from e-fuels vary greatly, as there is no universal answer on emissions as it depends on the individual production line and decisions around it, in addition to the source of the carbon dioxide (Ravi et al. 2023; Pasini et al. 2023; Lindstad et al. 2021; Scheelhaase 2019). The main factor in e-fuels emissions is the availability of energy produced from renewable energy sources as the fuel is only as green as the inputs to produce it (Ordonez et al 2022; Ueckerdt & Falko 2021). Power-to-liquid (PTL), a system in which power is taken directly from the renewable grid and turned into liquid components for industrial usage, has the highest potential for GHG emission reduction but is quite costly and requires a vast renewable energy production or grid (Skov et al. 2021; Andreasen & Sovacool 2021; Enevoldsen et al. 2021). Thus, when accounting for the required investments, the cost is exorbitantly high. E-fuels can still be produced without the PTL system but there is no guarantee of its CO_2 emission reduction. Additionally, the process is highly inefficient, requires hydrogen, and a way of extracting CO_2 from a source (DNV 2022b). This means that the large-scale adoption of e-fuels is still unachievable for the majority of nations (Gutierrez-Antonio et al. 2017).

Besides the variation in CO_2 emissions, synthetic fuels match their non synthetic (electro) counterparts in terms of high energy density, storability, transportability, and combustibility (Ballal 2023). These compatible properties mean that the transition can occur without the need to replace the vehicles (Rye et al. 2010). This same benefit is also the case for biofuels (Karatzos 2014).

Biofuel is the production of fuel from biomass such as corn, sugar, municipal solid waste, or alcohol (Callegari et al. 2020). There are multiple methods or processes to convert these feeds into the biofuel, the two most common are Fischer-Tropsch method (FT), alcohol-to-jet (ATJ), or sugar-to-jet (STJ) (Tiwari et al. 2023). However, the X-to-Jet can be converted to fuels with many types of biomasses, not only the two mentioned (Callegari et al. 2020). The conversion process involves complex chemical reactions through the introduction of hydrogen. The intricacies of these processes fall outside the scope of this project.

The important information and differences between the three production processes is the cost, and subsequent GHG emissions. ATJ and STJ are relatively cheaper options but are not carbon neutral while FT is most costly to operate and install but has a better carbon budget (Ballal 2023; Tiwari et al. 2023; O'Connell et al. 2019). So, economically speaking it is better to start with ATJ and STJ as they are cheaper but still reduce emissions compared to the traditional jet fuel. The cost of production of biofuel varies and consequently so does the price of the fuel itself as the decision for which feedstock to use has a great effect on the outcome. The feedstock decision contains externalities as if corn was to be the feedstock, there would a subsequent greater demand for corn leading to greater use of water and arable land causing unsustainable behaviour within the agricultural sector (Su-Ungkavatin 2023; Bai et al. 2012; Fischer et al. 2010). So, despite the environmental nature of biofuel it can have unforeseen and unintended consequences in other important industries.

Similar to e-fuel, biofuel retains comparable properties as traditional jet fuel. This means that both biofuels and e-fuels can be classified as 'drop-in fuels' (Pedersen et al 2022). This category of fuel, which can be deduced from the name, can be dropped into existing vehicles and infrastructure (Rye et al 2010). Thus, the barrier of transition to these fuels are less than the other fuels, at least in terms of economic costs (Pedersen et al 2010). Therefore, these are considered transitional fuels that bridge the gap between the current high emission reality and true zero future (Ydersbond et al. 2020). This is not the case for hydrogen.

Hydrogen has become the 'poster child' of green fuels due to its high energy content and (depending on the input in production) emitting only hydrogen which is not a greenhouse gas (Howarth 2021). Since there are no carbon molecules in hydrogen (H2) it is not as detrimental to the environment. However, much like in e-fuels, the input into the production line is the greatest factor in emissions. If the electricity used in the electrolysers (machines that produce H2) is not from a renewable source and there is no CCS function present in the production, then the CO2 emission reductions are negligible (Pedersen et al. 2022). This type of hydrogen is referred to as grey hydrogen. Blue hydrogen is when the power used in the electrolyser is not from renewable sources but there is CCS present, resulting in a less pollutant fuel. Lastly, if the power is from a renewable source it is referred to as green hydrogen as it is a fully carbon neutral production (Pedersen et al. 2022; Dawood et al. 2022). It is here that an important distinction has to be made, hydrogen fuels when transformed into jet fuel are e-fuel. Hydrogen fuel as referred to in this thesis focuses on liquid hydrogen fuel cells. Hydrogen is a required ingredient in the production of e-fuel and thus, most e-fuels are hydrogen derivatives. However, for the purposes of this thesis those fuels will be counted as e-fuels. When hydrogen is referred to, it is entirely liquid hydrogen.

Liquid hydrogen has different properties than the other fuels and thus, requires investment into new technology, storage, and planes (Brewer 1976; Brewer 2017; Pehr et al. 2001). Since all new infrastructure needs to be invested in and constructed it would seem illogical to consider hydrogen as a future fuel. That is until energy content is discussed, as traditional jet fuel has an energy content of around 44 MJ/kg while hydrogen in its liquid form has 120 MJ/kg (EERE 2022; Ministry of Defence 2019). Depending on the energy efficiency of the aeroplane, this would result in a third less usage (Choi & Lee 2022). Combining said fact with the 'true zero' (no emission) possibility for hydrogen and it becomes evident why it has been paraded as the future. There are two challenges to hydrogen and that is the aforementioned production as it needs to be from renewable energy sources, and the other is the cost of it. Hydrogen is expensive and, in most countries, there is not enough CCS nor renewable energy sources to produce the carbon friendlier alternative versions (Ajanovic et al. 2022; Ghaebi Panah et al. 2022).

The last energy carrier that requires some attention is the potential of electrification of the aviation industry. If all air transport used electricity as their energy source, the emissions would only be reduced if the electricity was generated through renewable / carbon neutral means (Zaporozhets et al. 2020). The technology is advancing towards being commercially viable but is yet to be advanced enough to garner response from the aviation industry (Gierulski and Khandelwal 2021). Electricity, as an energy carrier is not included in the model as regardless of structure, the model would need logic hard coded in to show technology advancement, availability of planes, and when the airports would start considering a transition. It would essentially be a planes become available in year X and are Y attractive equation instead of a dynamic calculation, hence electricity only being a talking point in the discussion. However, it is an important aspect in this transition and further research would benefit from including it.

1.2.2 Reference Modes

Due to the future-looking perspective of this project the reference modes will not be historical data on the issue as the dynamics have yet to occur. In Norway, Denmark, and Sweden there currently is no usage of SAFs in the fuel mix (Ydersbond et al. 2020). Therefore, the reference mode the model will be compared to are other forecasts or predictions for sustainable aviation fuels. This means that the goal is not necessarily to replicate the behaviour but rather discuss other perspectives on the topic.

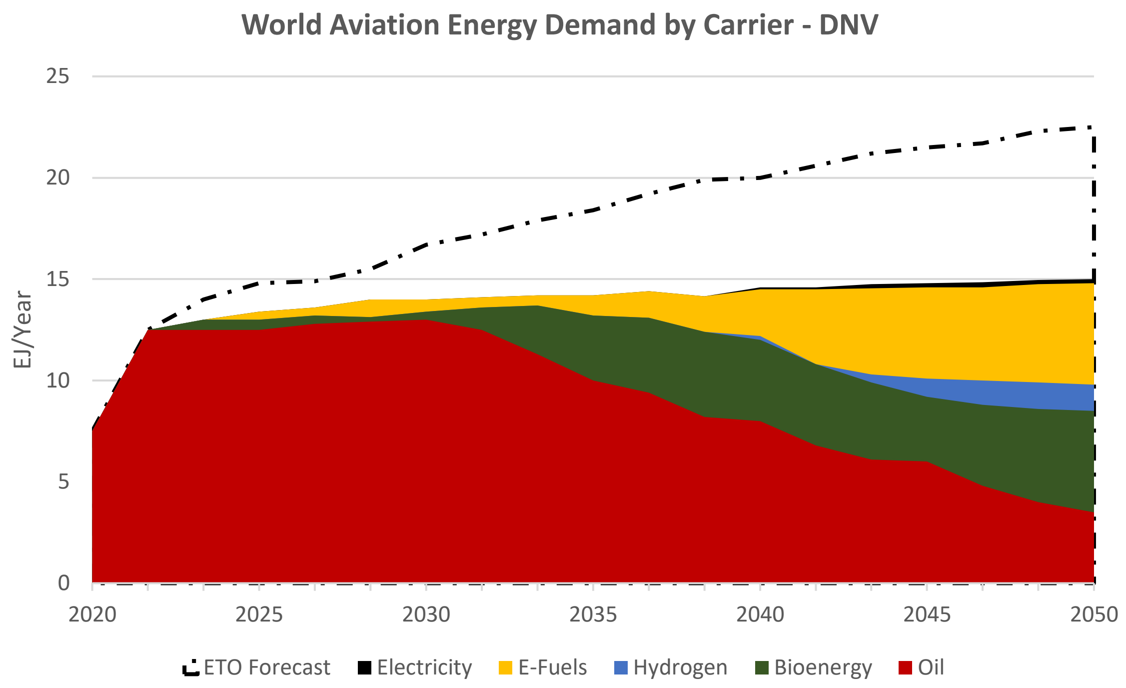

Figure 1.1 – DNV ETO World aviation energy demand by carrier 1990-2050

There seems to be an agreed upon behaviour where most forecasts or predictions start increasing around 2022-2025 (BloombergNEF 2022; ICAO 2022; DNV 2022). As *Figure 1.1* shows, most SAF seem to be introduced within that timeframe and increase increasingly but it seems to not grow too large by 2030. So, despite becoming available, they are not adopted until after 2030. This could be for many reasons, such as lacking infrastructure, production, and economically they cannot compete yet (BloombergNEF 2022).

Det Norske Veritas (DNV) (2022) forecasts using a system dynamics model that starting from the early-2020s biofuel (bioenergy) will start to be adopted, e-fuels by the mid-2020s, and hydrogen fuel by 2040. Electricity only becomes part of the share of the fuel in the late-2030s and only by a small margin, as the planes need to be rolled out before the demand can increase significantly. The sharp increase in energy demand from 2020 to 2023 is due to the recovery from COVID19. DNVs forecast shown in *Figure 1.1*, assumes there is a decline in aviation due to auxiliary policies and hence, a decline in overall energy demand. The DNV model assumes that despite the low efficiency of the e-fuel production there will be a need to start using e-fuels as they release less CO2 emissions than biofuel (generally). Thus, it follows the general trend of biofuel first, then e-fuels, and lastly hydrogen as energy carriers. In 2050 there is still a large demand for oil based fuels, or traditional aviation fuel (TAF) as this thesis will refer to it as. This stems from the slow adoption and production of SAF and the technology required for electricity and hydrogen (DNV 2022).

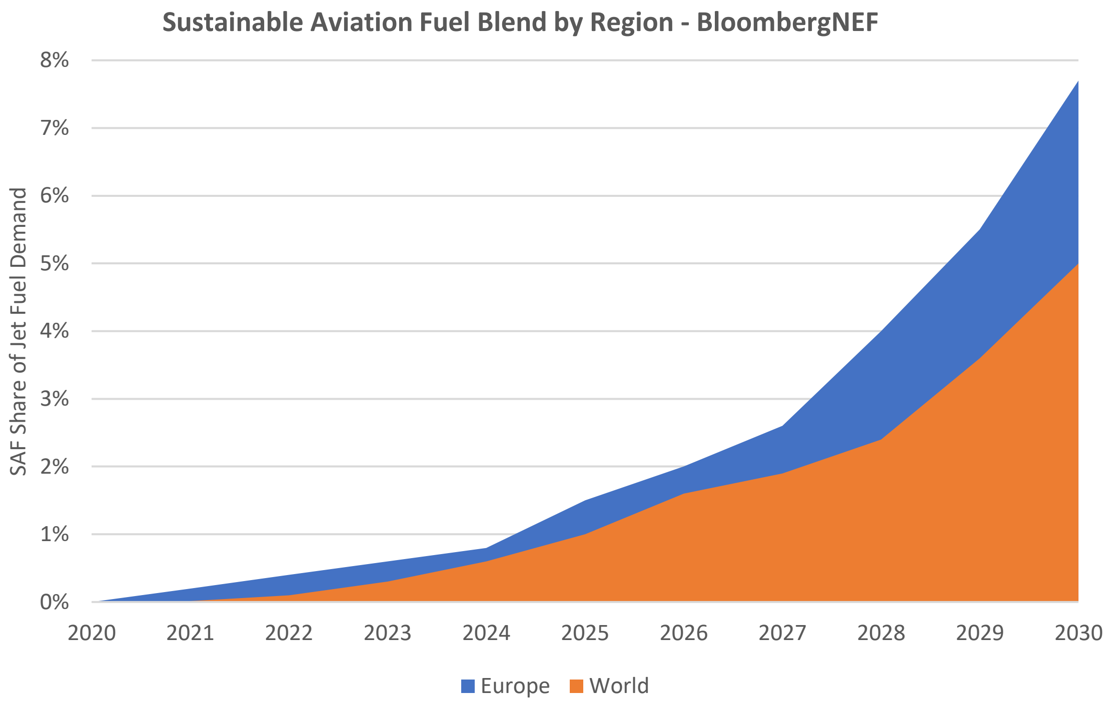

Figure 1.2 – BloombergNEF Sustainable Aviation Fuel Blend Forecast

In contrast, BloombergNEF, the research consultancy part of Bloomberg, focused on the share of jet fuel demand that is SAF and they conclude that by 2030 it will be closely below 8% of demand in Europe. This seems too optimistic as it would mean the adoption of SAF in 2022, which in the year 2023 we know was not the case. The second reference forecast is from the International Civil Aviation Organisation (ICAO) which agrees with the start of the transition but unlike BloombergNEF and like DNV they distinguish between the fuels and focus on civil aviation emissions instead (*Figure 1.3*). The emissions in each fuel scenario start to diverge from the 'Airport Technology Frozen at 2050 Level' (ICAO 2022). As this graph is forecasted into 2070 it shows that there is not a large increase of SAF, and no consequent decrease in emissions until after 2030. This seems more realistic as organisations are slow in transitioning. Biofuel is adopted first, followed by e-fuels, and lastly, hydrogen only becomes available around 2045. The late adoption of hydrogen related technologies seems accurate due to the of requirement of switching infrastructure and low levels of production. Emission by 2070 reaches an 87% reduction from the baseline scenario previously mentioned (ICAO 2022). The emission reduction is not only related to the switch to greener fuels but also an increase in fuel efficiency which is a crucial aspect to the system but outside the scope of the model. This prediction is taking a global perspective but if this was the forecast for Scandinavia then none of the countries would have reached their climate targets (EP 2021a; Royal Norwegian Embassy in Jakarta 2022; UM 2022).

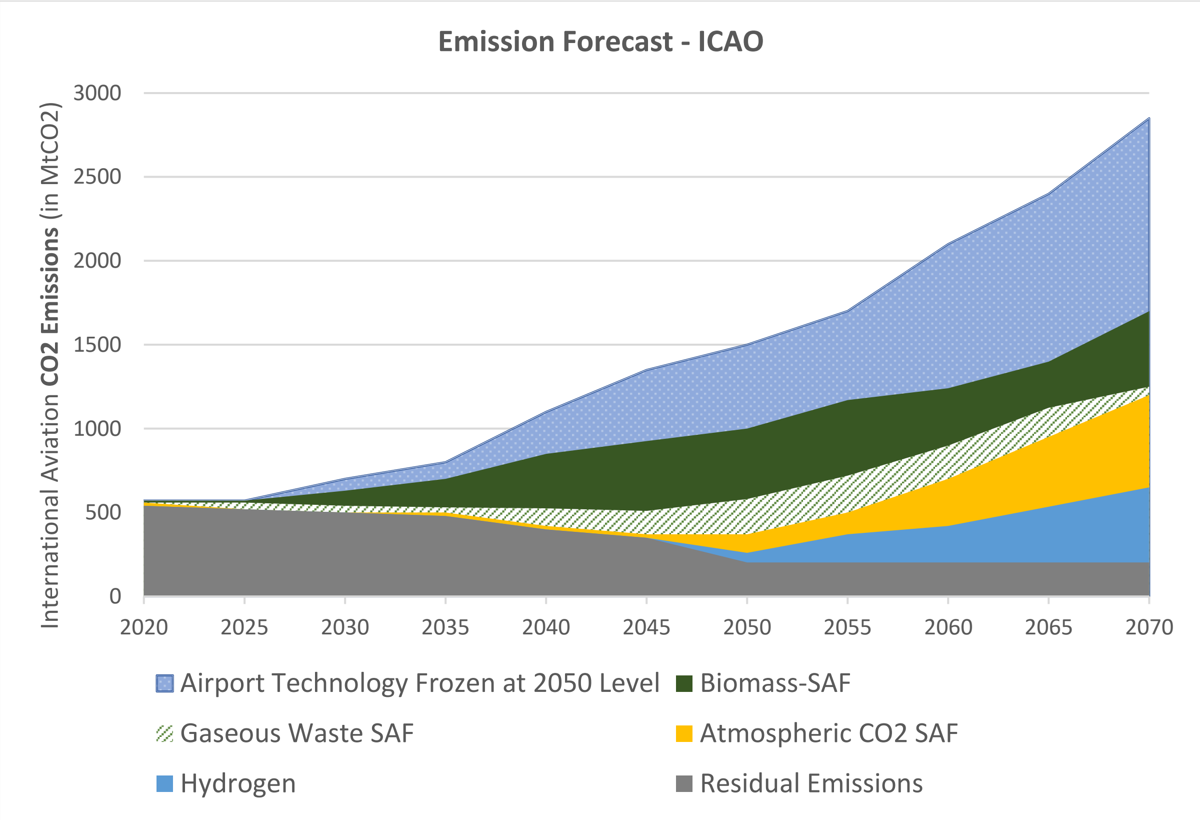

Figure 1.3 – ICAO Emission Forecast with Fuel Transition

The model created for this thesis will not account for CO2 emissions from operations or airports, it will only focus on the emission from the burning of fuel. However, the ICAO (2022) prediction behaviour of the graph seems more realistic compared to the BloombergNEF (2022). The exponential growth displayed in BloombergNEFs forecast (2022) (*Figure 1.2)* seems unrealistic as that would consist of constant transitions rather than large ‘plunges’ with sudden switches of fuels. Accounting for the ‘human factor’ in these decisions there could be delays and decisions that in hindsight could have happened earlier resulting in a larger jump which can be seen with ‘Biomass-SAF’ in *Figure 1.3* (ICAO 2022). Regardless, the trend between the predictions displays a slow but exponential start to the transition. Both organisations state that they are assuming no policy intervention such as blending requirements, taxes, or carrot-and-stick tactics as those can affect these decisions and are already being considered on an EU-level (EC 2023).

1.2.3 Sustainable Transitions

The sustainable aviation fuel transition is part of the greater body of literature on sustainable transition. Although SAF will face unique challenges in the aviation industry, it is beneficial to see what lessons or challenges can be studied from the whole sustainability field. This section will describe in short, the literature of sustainable transitions and the challenges and opportunities that have been found and relate it to SAF.

The urgency of transition due to the rapid increase in climate change has caused an increase in the study of sustainable transitions to new frontiers (Markard et al. 2012). From its early roots, the literature has been focused on socio-technical systems (Markard et al. 2012). These systems are networks constructed of institutions, firms, regulators, and individuals (Weber 2003). These networks are interdependent on each other, and the decisions made by individual network nodes or participants reverberate through the network (Weber 2003). The result being that a transition has to be able to convince or force each actor in the network to a specific future that may be varyingly beneficial to them (Geels 2017). Hence, the complexity of transitions as the subsequent discourse from the transition creates delays that decrease the speed of the transition itself. No institution, private or public, will sacrifice power and financials to complete a transition (Green 2018).

The framing of sustainable transitions in socio-technical systems focuses on two important aspects: 1) social discourse and debate about the transition and 2) the technological advancement aspect (Markard et al. 2012). The social aspect revolves around the discussion of who will be the ‘loser’ in the green future (Bridge 2023). If the technology to transition was available tomorrow it would still take years to decide on implementation, as it is not always within a group of people’s best interest to transition. Transitions better the planet but the details of those plans are of high scrutiny and contention (Sansilvestri et al. 2021). The social aspect also constitutes the social domains such as the working and everyday lives of the populace.

The technological aspect is the change in technology required to allow for the transition. In the case of aviation an example is the creation of hydrogen planes. For transitions to occur there needs to be a perceptive and structural change in the system to the new technology. In terms of general transitions, it could be wind turbines that need to be connected to the grid and the necessary infrastructure surrounding them. In terms of SAF, it relates to the infrastructure that surrounds it and greater efficiency in the process. For the fuels to be truly carbon reductive or neutral fuels, they either have to be transported in carbon neutral vehicles or be produced on-sight (DNV 2019). These obstacles mean that the framework also needs to be constructed prior to any switch to an alternative fuel. This further creates interdependencies in the socio-technical system, as now the transport part is included, so for the one industry to transition others need to do so as well. This thesis is mainly concerned about the economical / technical aspect of the transition and the societal part is referred to in the underlying assumption.

1.2.4 System Dynamics and Sustainable Aviation Fuel Literature

The urgency of climate change has spurred both the academic and private sphere to research sustainable transitions. This is definitely not the first research into sustainable aviation fuel, nor will it be the last. However, in the simulation based methodology literature little attention has been placed on SAF and its demand. A lot of the focus has been instead on electric vehicles on the road (Rodrigues et al. 2012) or sustainable transitions in general (Laimon et al. 2022; Saavedra et al. 2018; Struben & Sterman 2008). The few articles that use modelling for the aviation industry tend to focus on airport and fleet dynamics (Shepherd et al. 2014; Talwar et al. 2021; Peng et al. 2021; Gomez Vilchez & Jochem 2023). When the focus has been on the fuel its focus has been on the production and supply side (DNV 2022; Safiei et al. 2015; Petterson et al. 2013).

Martinez-Valencia (2021) constructed a system dynamics model for the configuration of supply chains for SAF and concluded that the SAF supply chain does not entirely fit into any previous supply chain category due to its emerging nature. The main takeaway being that the supply side requires more revenues to scale up, as currently there is not enough demand to ramp up supply. In general, the trend in simulation work is to focus on supply-side modelling and there is therefore, a gap in the literature for simulation-based demand-side modelling.

1.3 Methodology

1.3.1 Models & Predictions

Models are not a new tool used in the toolbelt of researchers. Arguably, they have existed for centuries in mental models (Johnson-Laird 2004). Mental models being defined as individuals process of reasoning when trying to "envisage the possibilities compatible with what they know or believe" (Johnson-Laird 2012, p131). In other words, it can be described as the analytical part of the thought process where the perception of the outside world is the input into that equation. The computation or simulation models are thus, the logical continuation of that mental process. Instead of thinking that there exists a correlation between variable X and Y, it can be calculated with math or programs (Rosen 2013; Goldsman et al. 2010). Typically, these methods of calculating focus on a linear perspective, i.e., what is the correlation between X and Y (Ogata 1978). System dynamics is unique in that regard as it introduces feedback and nonlinearities into these calculations.

Feedback is the reaction to a change in anything (Ramaprasad 1983). An example being that a worker receives a negative response from their boss in relation to a task they submitted. The worker then takes that feedback and improves on the next task resulting in the boss giving a better response resulting again, in the worker performing better. This is a feedback loop. Feedback loops are a continual process in which changes in one part of the loop reverberate through the loop eventually affecting the original change (Barlas 2007). These can be negative or positive in nature. Taking the previous example, if the worker takes the feedback harshly and starts to perform worse, the feedback will only become worse resulting ultimately with horrendous output.

These feedback loops are not closed entities, they interact with each other to form complex systems (Barlas 2007). The resulting web of complexity is the result of the interconnectedness that originates from the interaction between the feedback loops. Feedback loops are prevalent in all aspects of life, be that underlying, such as the natural system, or in a more presenting way as in the workplace example (Plahte et al. 1995). Thus, interlinkages between the loops are 'systemic' as they constitute systems (Thomas 1978). System dynamics or systems thinking aims to quantify these inter-relationships between feedback loops (Forrester 1994).

It is due to this reason that system dynamics is a suitable methodology for examining the demand for sustainable aviation fuel in the Scandinavian countries. The sheer number of decisions, information, processes, and paradigm shifts that concur ensure that there is no such thing as a non-complex transition (Crespi 2015). This additionally, leads to a higher risk of unforeseen consequences.

Creating a quantifiable model that can demonstrate the insights of a nonlinear system could aid policymakers and companies to make better decisions going forward. That is not saying that this model or any model for that matter is a full solution (Stainforth et al. 2007). Models are tools that can help give insights into how problems or solutions will develop and what can occur under these circumstances, it is not a silver bullet solution that should be taken at face value (Vickers and Elkin 2006).

Because of this, system dynamicists are wary of using the word ‘predict’. The concept of predicting seems to hold sanctity reserved for those with full information in any situations. No model will ever be able to cover and fully predict the future of any system or development that they are focusing on, uncertainty and risk will always be a factor (Fisher et al 2019). However, there should not be such aversion to the word predict, as that is what occurs on a daily basis. Thinking about how one’s day will go, and planning accordingly is using one’s personal mental model to predict the behaviour of the day and plan accordingly. Thus, constructing a mathematically sound model to predict the behaviour of a system is the same but on a larger scale (Langarudi 2023). The mental model and quantifiable model are both tools to predict the behaviour or events that will occur today or in 50 years, they are simply a tool to aid individuals, groups, or institutions to make more informed decisions. Senge and Forrester (1980) suggest that the validity of a model is derived from the “...confidence in a model’s soundness and usefulness as a policy tool.” (Senge and Forrester 1980, p8). Relating this to the act of predicting behaviour then the usefulness and validity can be said to be derived from the models’ insights that come from its predictions of the behaviour.

To conclude, the reason system dynamics is the methodology decided upon is due to its systemic method of reducing complexity through feedback loops (Sterman 1992; Gillespie et al 2004). Taking a web of interdependencies and being able to clearly and concisely communicate the findings and mechanisms that can alter the intended effect is almost a necessity in respect to analysing green transitions. There is no such concept as an easy, painless sustainable transition, the multitude and magnitude of the decisions that are needed will inevitably cause strain in other aspects and give headaches to any decision maker. The hope is that with tools that can reduce the complexities and provide insights to these decision makers, such as a system dynamics model, their headaches are at least not migraines.

1.3.2 Data Collection

Models do not appear out of thin air, they are first conceptualized and then informed by parameters, structure, and behaviour (Sterman 2010). The behaviour is usually then compared to data to validate the structural behaviour of the model and whether it is ‘able to replicate the reference mode’ (Sterman 2010). The same data, or more commonly other values, are used to infer the parameters and structure. These could be from interviews, calculations, other researchers, or calibrated to best match the reference mode. Regardless, the models are not conceived only from the modellers own conceptualization of the system. In fact, finding other research, data, and or equations that can be worked into the model can increase the perceived validity of the tool as it is then "…standing on the shoulder of giants" (Newton 1675). The data that was collected and used to inform the sustainable aviation fuel model consisted of secondary sources, statistics from the three countries national databases, and most importantly, data provided by DNV. The values and references for each parameter and structure can be found under Appendix C: Model Documentation.

1.4 Dynamic Hypothesis

The dynamic hypothesis is the conceptual structure of the model, in other words, the structure without the equations. It conceptualises the system to show the insights and feedback loops that inhibit the structure in an abstract aggregated map (Saeed 2017). So before going over the model, the structure, and the aggregated mechanisms that drive the behaviour are explicated. The mechanism in system dynamics are the feedback loops presented. Hence, each loop is explained in terms of mechanism, behavioural tendencies, reasoning, and justification. The model is arrayed per country and per fuel, this means that the structure presented essentially contains 12 layers of structure (3 countries * 4 fuels). It will be highlighted when these layers interact in a comparative and competitive sense.

The names indicate either individual variables or sections of the model that are crucial to its behaviour. The arrows indicate a causal link in the direction that the arrow is going. So, if the arrow has a plus sign (+) between variable A and B it means that if A increases so does B. If the arrow is a minus sign (-) then when variable A increases B decreases. These arrows then are interlinked between each other so that A leads to B leads to C leads back to A.

$$A \rightarrow B \rightarrow C \rightarrow A$$

This is then a feedback loop as an initial change in A reverberates through the link back to A resulting in an increase or decrease. If an increase in variable A results in a further increase in A, then it is a reinforcing loop as it reinforces either growth or decline. If an initial increase in A result in an eventual decrease in A, then it is a balancing loop as the variable is adjusting to another structure or source.

B1 -Balancing Demand through Price

An important aspect to the system is the exogenous air travel demand which is driven by gross domestic product per capita (GDP pc) and population. The relationship between GDP pc and population were provided by DNV and calibrated in the model. As GDP per capita increases, so does air travel demand as the countries are becoming richer and thus, want to travel further and more frequently.

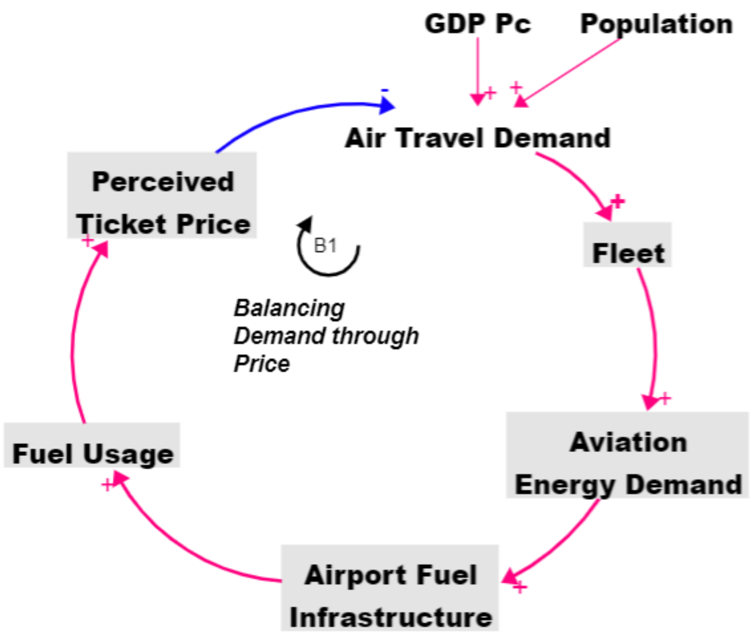

Figure 1.4 – CLD: Balancing Demand through Price

Air travel demand causes the airline companies to increase the size of their fleet to be able to meet the current demand. The increased fleet has a larger energy demand which results in the airport needing to construct more fuel infrastructure (namely storage). The cost of the construction is then passed onto consumers who compare the price of tickets from one year ago, and if it has increased then some may choose to either travel by other means or stay home for the vacation. The resulting loop means an increase in 'Air Travel Demand' eventually decreases it as the cost of expansion is passed onto the consumer, thus, making this a balancing loop.

B2 – Balancing Emissions to Fuel Usage

Different types of fuel release different amount of CO2 and therefore, fuel usage has vast effects on emissions. As the base case is traditional jet fuel, any change in fuel usage indicates a change towards more sustainable options thus, decreasing emissions. The prospect of decreasing emissions gives SAFs an attractiveness that traditional jet fuel cannot possess. 'Fuel Attractiveness' is a simplification of the fuel comparative aspect, as in this is where those layers of the model interact to compare the attractiveness of all the fuels and then start to invest in the most attractive. Due to the varying energy properties of the fuels, it affects demand which leads to an increase in the required infrastructure.

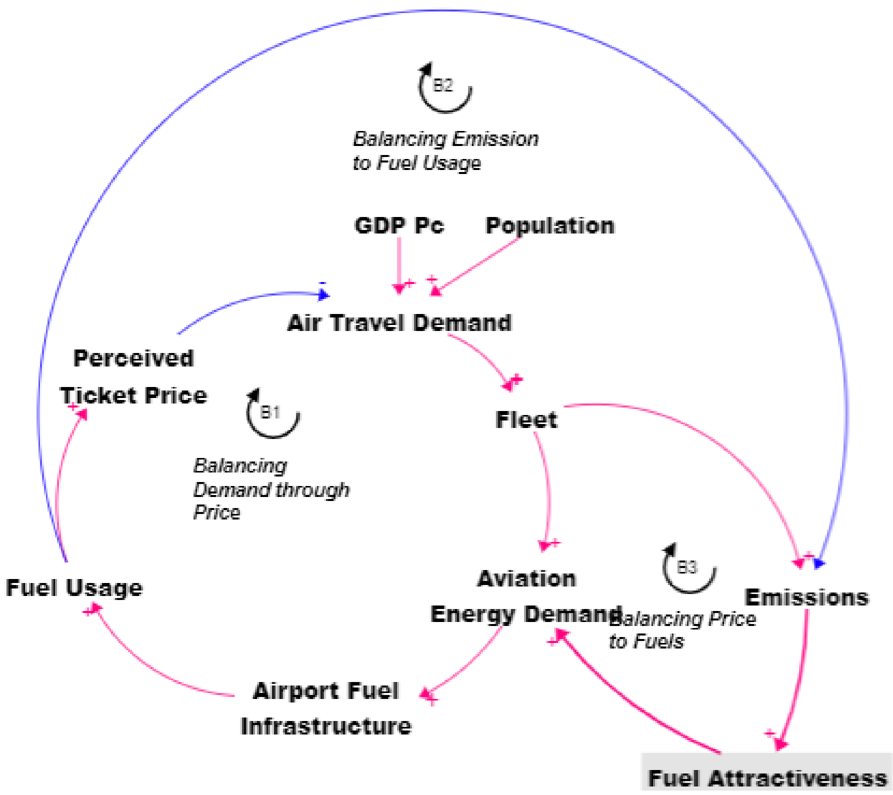

Figure 1.5 – CLD: Emissions

The increasing infrastructure then affects the fuel usage. This varying structure means that in the case of SAF this is a reinforcing loop but for the base layer / scenario it is a balancing loop as it results in the decrease of traditional jet fuel.

B3 – Balancing Price to Fuels

Figure 1.5 introduced an additional loop. The loop / mechanism aims to adjust the perceived price to which fuel is being used. The greener fuels will affect the price of tickets as they are (currently) more expensive when compared to the traditional jet fuel so any transition will cause those extra costs to be passed onto consumers. The result is a loop that when the fleet increases and starts to emit more, the fuel attractiveness consequently increases as the emissions (according to the nations climate targets) are too high. The consequence is thusly, that the airport starts to provide access to SAF earlier resulting in a higher ticket price and thus, decreased demand temporarily.

B4 – Balancing Price of Fuel to Demand

An increased demand for a specific fuel according to the basics of economics means it is more valued as there is a larger need for it. When demand for SAF increases the price of it does as well which makes it less attractive of a fuel as it costs more. Companies are not by nature, charitable and the sole goal is to seek profits. Purchasing a more expensive fuel in the presence of a cheaper one is rare unless the benefits are worth it. The B4 loop ensures that if a fuel becomes attractive the price of it will increase and thus represents a simple market mechanism of supply and demand.

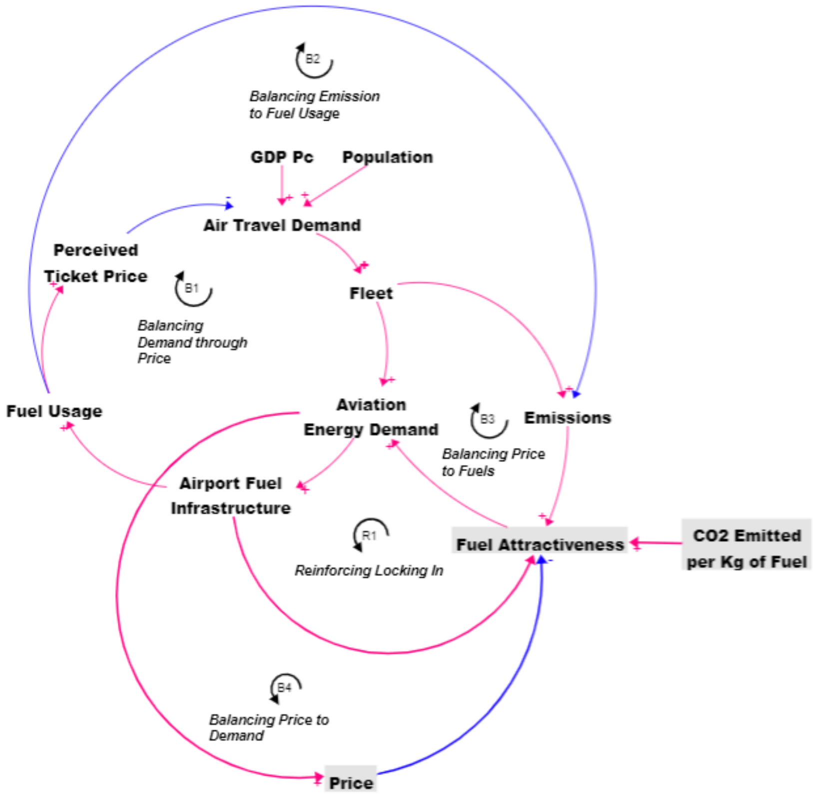

Figure 1.6: CLD: Price of Fuel and Cost of Transitioning.

R1 – Reinforcing Locked in

The economic nature of companies means that they are aversive to paths that will result in spending, especially if the status quo is sufficient. It is expensive to plan, order, and construct new infrastructure, thus, airports are prone to being ‘locked in’ into certain fuels. This reinforcing loop counteracts the attractiveness of any new fuels as the infrastructure that exists locks the aviation industry into the specific fuel.

B5 – Balancing Price to Supply

The demand aspect of the supply-demand mechanism exists within loop B4 and B5 is thus, the supply aspect. The production is driven by two aspects: the renewable energy sources and if the aviation industry is using the fuel. When the fuel usage for any fuel increases then the production of it does as well, as there is an increase in demand incentivizing expansion of the supply side. According to supply demand mechanisms this will reduce the price, and consequently increase the attractiveness of the fuel.

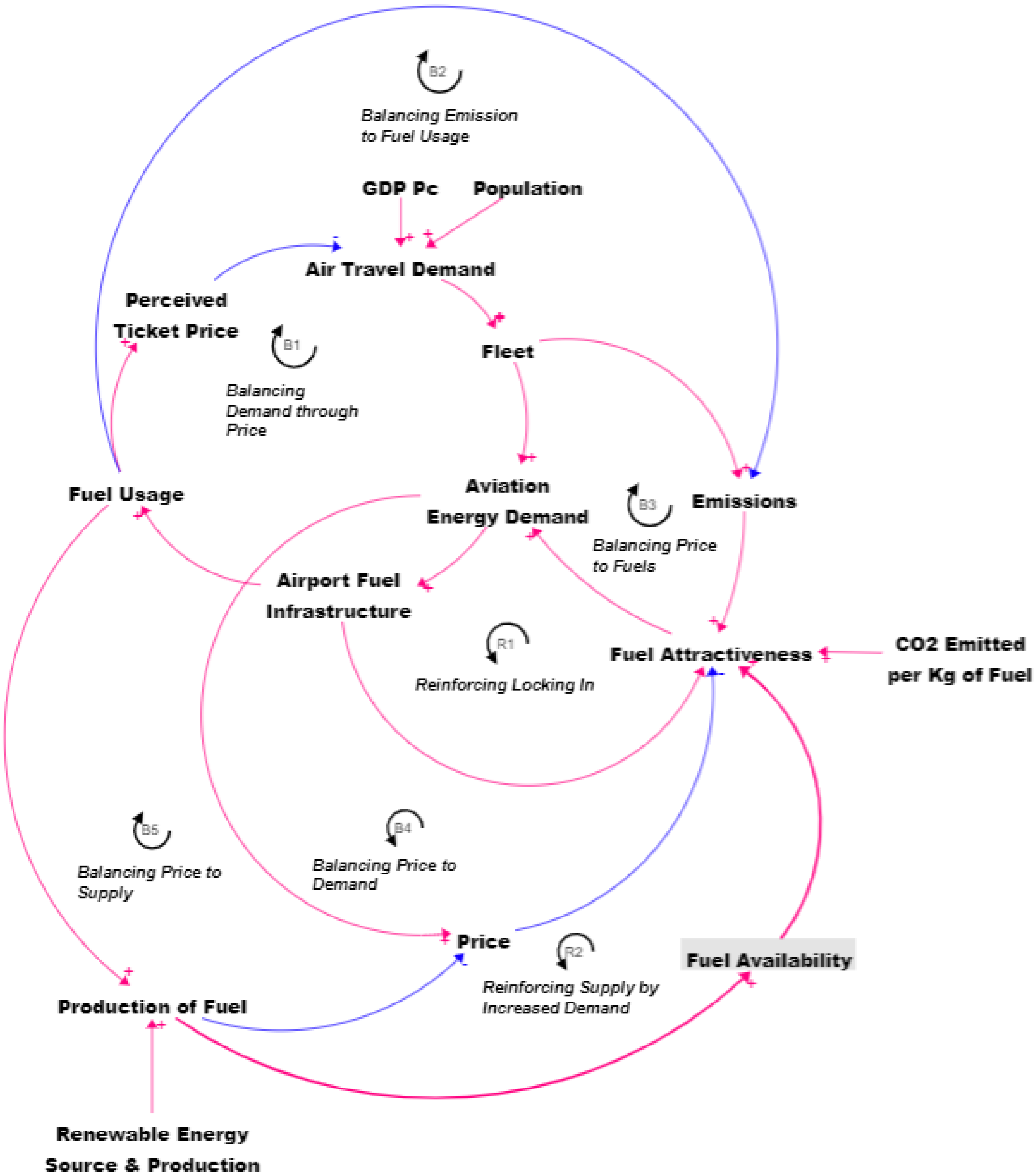

Figure 1.7 – A Completed Dynamic Hypothesis

R2 – Reinforcing Supply by Increased Demand

Fuel attractiveness is a function of availability, as regardless of the attractiveness of a certain fuel, there can be no transition if there is insufficient supply. An increase in the production of fuel results in more fuel availability as there is a larger production capacity. This allows the fuel to be more attractive as there is sufficient supply to meet demand. So, the transition to the new fuel further increase demand for the fuel which spurs further expansion on the supply side. This expansion means there is more fuel available which further makes it attractive to the airports. It is reinforced economic growth measured in fuels.

The Loop Interactions & Drivers of Demand

The main drivers of the model are price, emissions, availability, and cost of transition. These aspects are the decisive drivers of the fuel attractiveness and consequent transition. The loops that are the foundation of these drivers are the following:

Price – B4 and B5

The balancing loops B4 and B5 represent the supply and demand side of the market. If the supply increases, then B4 reduces the price to its equilibrium status. If demand increases B5 will increase the price to match the increased demand to a certain extent. In terms of effects B4 is much stronger than B5 as the supply has a lot of 'space' to grow (i.e., increase capacity) compared to demand as demand will never equal to production capacity. The strength of B4 is derived from the fuel production capacity, the more capacity the cheaper the price due to B4. When the price is cheaper the specific fuel becomes more attractive which increases demand and supply as the market responds to the demand by increasing production. Thus, despite B5's nature to decrease the strength of B4 it cannot effectively do so as its driver (demand) also is a part of supply.

Emission – B2 and B3

Emission drives the model through its emission targets. If the emissions are too high, then the attractiveness of SAF becomes stronger as the aviation industry is off their targets. B2 is the adjustment of annual emission to the fuel that is being used. So, if hydrogen dominates the fuel share, B2 decreases emissions since hydrogen can be a non-pollutant fuel. So B3 is adjusting the emissions to the fuel share. B3 adjusts emissions according to the fleet. The larger the demand for flights, the larger the fleet will become and thus, emissions will increase. B3 will only lose its strength if the entire fuel share is from a non-pollutant fuel otherwise there will always be increasing demand and thus, increasing emissions.

Availability – R2

Fuel availability is based on the fuel production capacity so the larger the production capacity the larger the fuel availability. Fuel capacity is driven by two aspects, the exogenous renewable energy production and fuel demand. As energy production from renewable energy sources is exogenous only R2 drives availability. Once a fuel has become attractive enough and starts to become part of the fuel usage, the supply side notices this and starts to ramp up production for the expected demand increase. The increased production reinforces the fuel availability and consequently makes the fuel even more attractive. Thus, the reinforcing loop R2 drives the fuel availability.

Cost of Transition - R1, B1, R2, and B5

The cost of transition is the cost of constructing all the infrastructure it would take to meet the demand with only the specific fuel. R1 reinforces the dominant fuel as the airports are 'locked in' into specific infrastructure and thus, the cost of transition grows exponentially as demand is increasing. The more demand, the more expensive it is to transition and thus, the less likely the newer fuels (mainly hydrogen) are to be adopted. The cost of transitioning is counteracted by the other drivers, if the only aspect that was being examined was cost then there would be no transition but as there are other factors, namely price of fuel and environmental benefits, eventually R1 loses its strength and switches to the next dominant fuel and locks that in. So, in summary R1 is counteracted by R2, B1, and B5 since it allows the R1 loop to switch the fuel the aviation industry is locked into.

Chapter 2: Model Structure & Validation

2.1 The Model & Assumptions

The dynamic hypothesis is the conceptual version of the model intended to give an overview of the feedback loops and main structure/indicators. Operationalising the model through the addition of differential equations allows for hypothesis testing to discover the simulation space for the system of feedback loops. The simulation space is the variation in behaviour in response to the alteration of the parameters, which needs to exist within reasonable or expected behaviour (Barlas 1996; Sterman 2010). If the output of the model is unexpected and illogical, the confidence in the insights of the model is worsened as the robustness of the model is flawed (Schwaninger & Grösser 2020). All SD models (and models in general) should be producing logical behaviour for the right reasons (Barlas 1996). Hence, the simulation space should be logical, and in accordance with the decision rules placed on the model (Morecroft 1988). That is not to say that unexpected behaviour raises doubts about the model, as unexpected behaviour could be an insight, it is rather that behaviour that physically should not be happening that should raise doubts. For example, if there are no workers in the model then there should not be any work being done.

In this section the model structure will first be delved into deeper and then secondly tested according to the framework laid out by Barlas (1996), Sterman (2001), and Senge & Forrester (1980). This includes dimensional, behavioural, structural, and extreme tests to see whether the simulation space is robust. As the model is relatively large, the following section is an overview covering the main structures and important assumptions, more information about the structures can be found in Appendix C: Model Documentation.

2.1.1 Aviation Demand Sector

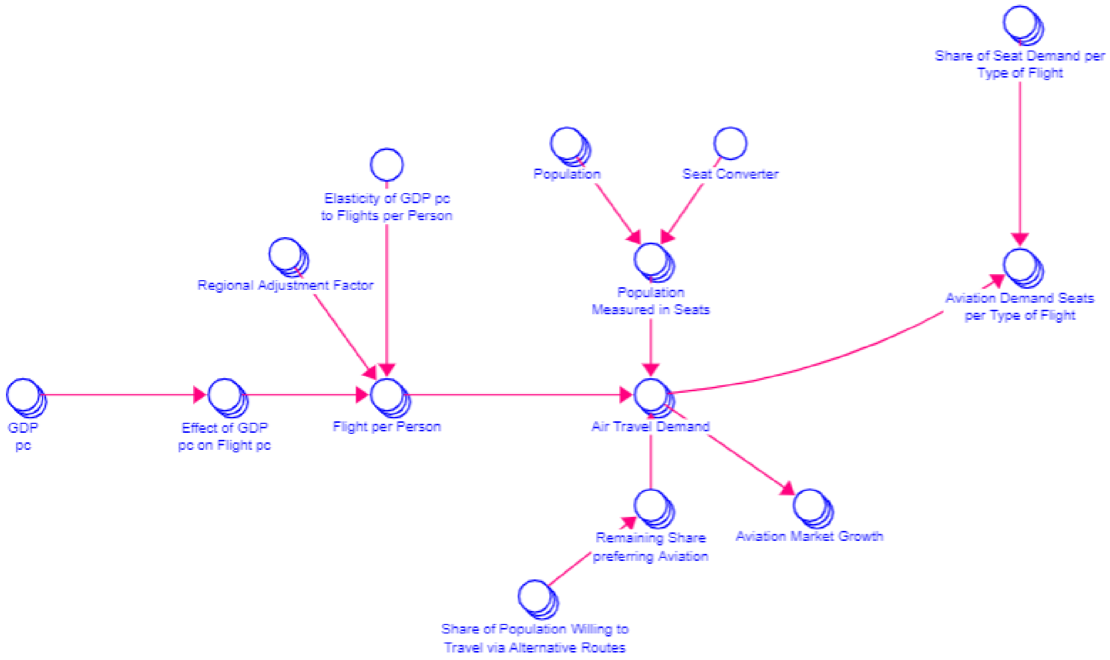

Figure 2.1 - Aviation Demand Sector

The aviation demand sector is based on the work of DNV and is exogenously driven. The GDP per capita is the purchasing power parity measured in 2017 USD provided by IMF (2023). The equation for air travel demand is given as the following:

$$Air\ Travel\ Demand = Population$$
$$* \left(Regional\ Adjustment\ Factor * (GDP\ PC)^{Elasticity}\right)$$
$$* \text{ Remaining Share Preferring Aviation}$$

It represents the flights per person multiplied with the population. Thus, giving the yearly average flights per an individual in civil aviation. *Figure 2.2* shows the calculations based on the following equation compared to the reference value in 2019 (Our world in data 2019). There was a lack of data on flights per capita and thus, the reference value is included as confirmation that the behaviour of the model is consistent with reality. Norway is half a trip lower, but as raising the ‘regional adjustment factor’ to equal the 2019 value caused the trips to become too many, too quickly and thus, the undercalculation is deemed acceptable.

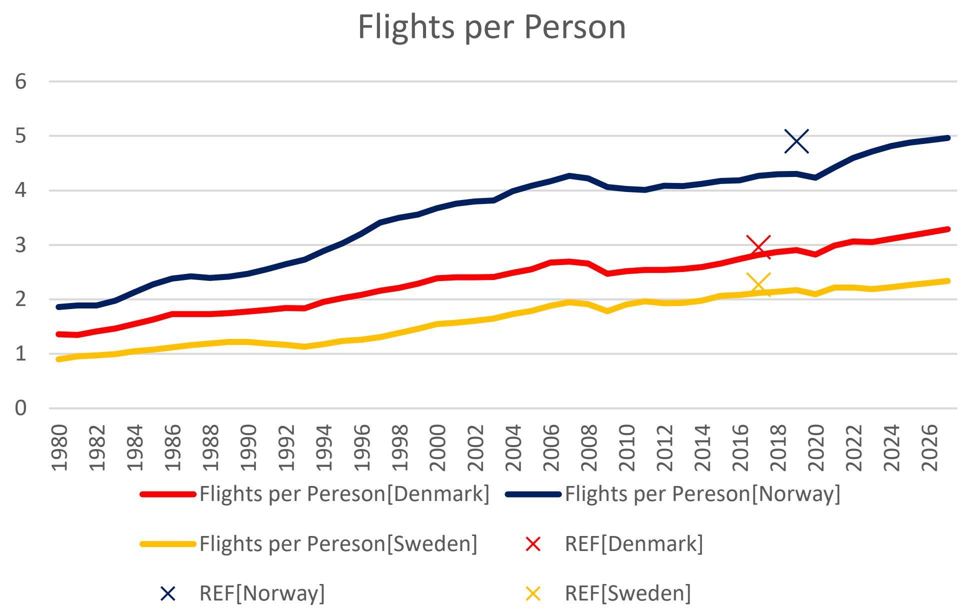

Figure 2.2 – Reference Flights per Person Comparison

Norway has the most flights per capita which is a result of its geography, as driving and trains take much longer compared to flying. As an example, Bergen-Oslo is a 50-minute flight or a 7-hour train ride. Comparatively, the same distance either does not exist in its smaller neighbours, Denmark and Sweden, or the train infrastructure is better connected, likely due to not having to tunnel through fjords. This is then multiplied by the share of demand per type of flight which has the following parameter:

Type of Flight	*Distance*	*Share of Demand*
Short Haul	<1500km	60%
Medium Haul	1500km<3500km	30%
Long Haul	3500km<	10%

Table 2.1 – Share of Demand

These values are used to divide the fleet into their respective categories of short, medium, and long-haul flights. The given values were calibrated and based on research by Ydersbond et al. (2020). Short haul flights are the most common which becomes clear when viewing the distance that a short haul flight encompasses (See *Figure 2.3*). The distance means that business, vacation, and commutes are included within this category (Beiger et al. 2007). The categories of flight contain different drivers as long-haul trips are undertaken for different reasons than the short haul flights (Beiger et al. 2007), however, as the model is not concerned with air travel demand this will not be elaborated upon.

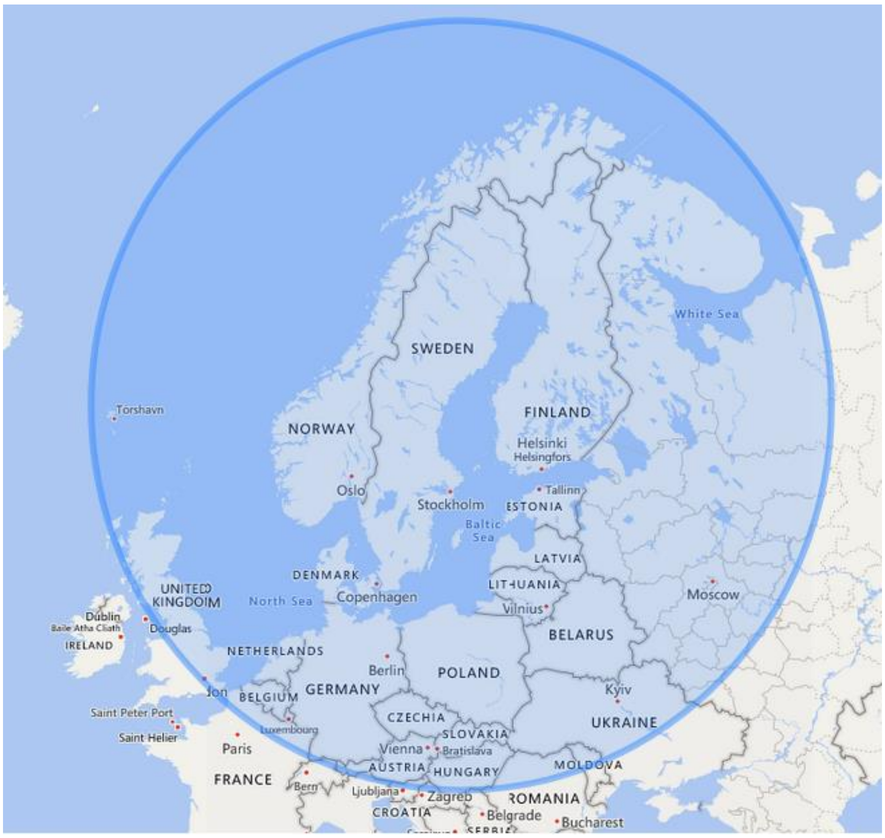

Figure 2.3 – The distance for short-haul flights based on a hypothetical airport located in the centre of Sweden.

2.1.2 Fleet Sector

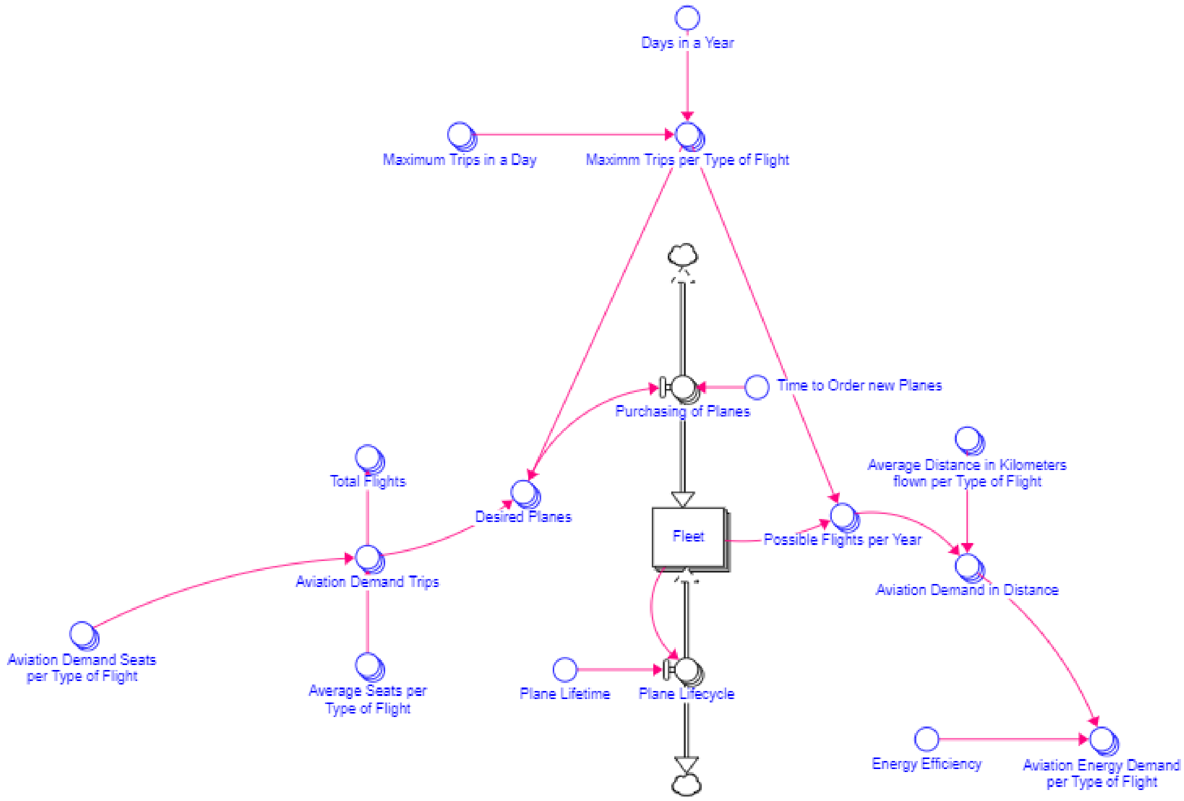

Figure 2.4 – Fleet Sector

The sector represents the increase or decrease in total country wide fleets based on demand. Realistically it is not a country fleet but rather based on the companies, thus, the stock of fleet is assumed to be based on only Scandinavian based companies, namely SAS, Norwegian, and Widerøe. It is aggregated to the national level as it falls outside the model boundary to account for the airline companies. These companies were chosen as they represent between 50-85% of the market share in Scandinavia (Ydersbond et al. 2020). The other national companies such as BRA flights in Sweden do not constitute a significant enough share to account for large discrepancies, thus, they were removed from the dataset (Ydersbond et al 2020). It is important to note that the model only concerns itself with departures as to not double count any flights. A flight from Oslo to Copenhagen would count as both an arrival and departure as its departures Oslo and arrives in Copenhagen. Thus, removing arrivals avoids said concern.

To find the desired fleet size, firstly, the amount of demand measured in seats is divided by the most common flight models per category. The equation is thus:

$$Aviation\ Demand\ in\ Trips = \frac{Seat\ Demand}{Average\ Seat\ per\ Type\ of\ Flight}$$

The average seat per type of flight is based on the fleet of the three aforementioned companies (SAS, Norwegian, and Widerøe). Data regarding the current fleet was viewed to find the share of flights belonging to each category followed by seeing which model of airplane was most prevalent. The following results were found:

Category of Flight	*Model of Airplane*	*Seats*	*Value in model*
Short-Haul	CRJ-900	80	80
Medium-Haul	Boeing 737	140	140
Long-Haul	Airbus 330	330	280

Table 2.2 – Seat per Airplane

The value in the model is different for the long-haul as the market was almost evenly split with a less seated model and thus was reduced to 280 (SAS 2023; Norwegian 2023; Widerøe 2023). Calculating the aviation flights from the seat demand is then converted into the desired planes based on the maximum possible trips per category. The formulation is based on the median flying time per type of flight being 1.5 hours for short and 4.5 for medium haul flights. The process on maximum trips per day is to find the time that flights can occur which is usually from 06 in the morning to 24 at night (18 hours). The question then is how many median time flights per category can fit into the 18-hour window.

The process to formulating the maximum long-haul trips was different as they do not neatly match the 18-hour window. The longest flight in Scandinavia is Copenhagen to San Francisco which has a duration of 12 hours so, the median time is 9 hours. The following calculation was thus performed:

$$Maximum\ Long\ Haul\ Flights\ per\ Day = (9\ Hours * 8\ Trips) = 72\ Hours$$

$$72\ Hours = 3\ Days$$

$$\frac{8\ Trips}{3\ Days} = 2.6666..Trips\ per\ Day$$

Based on said calculations, long haul flights can on average fly 2.6666 trips per day, this was then rounded down to 2.5 for simplicity. All the formulations assume there is little to no time between boardings as airline companies want to be as efficient as possible between flights. Consequently, these numbers are then used to calculate the number of planes needed to meet demand.

The next step is finding the kilometres travelled annually which is based on the fleet and median distance for each category of flight (see *Table 2.1*). The kilometres flown multiplied with the energy efficiency then gives the annual energy demand per country. The energy efficiency, the amount of energy used per kilometre is based on current models of plane traveling on Jet A-1 which results in a 464 MJ/km.

Energy efficiency is a complex equation to capture as it is affected by a plethora of factors, the weight, wind resistance, essentially any factor in the flight may affect the equation. Additionally, the efficiency varies during take-off and landing.

2.1.3 Emission Sector

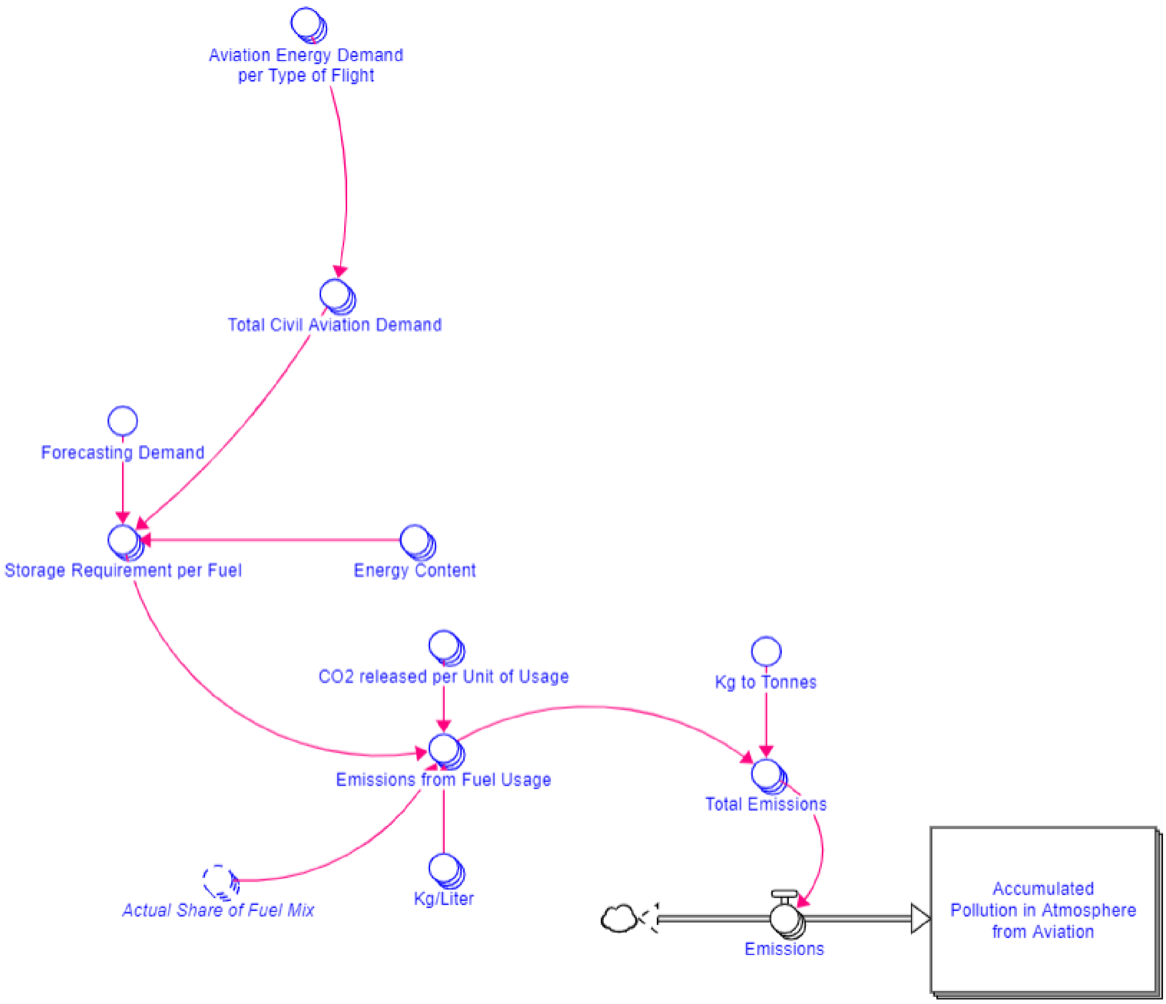

Figure 2.5 – Emission Sector

The emission sector is the smallest sector and is only concerned with the emissions from the fleet depending on the fuel used. Emissions is a key performance indicator (KPI) to see whether the countries are able to meet their emission targets. Targets that are all set to be carbon neutral by 2050 (EP 2021a; Royal Norwegian Embassy in Jakarta 2022; UM 2022). The parameters of energy content (the amount of MJ produced when the fuel is ignited per kilogram), and CO2 released per kg of fuel burned (CO2 equivalent) are based on literature and meet all the fuel standards (Ministry of Defense 2019; Herrell 2022; Li 2022; Gofman 2003; EERE 2022; New Zealand Government 2019; Llewellyn & Miftakhov 2022; Yoo et al. 2022; De Joing 2017; M Ballal 2023). The following variables are given for those parameters:

Fuel	*Energy Content (MJ/Kg)*	*Co2e Released per Kg*
Traditional Jet Fuel	42.8	2.63
Liquid Hydrogen (LH2)	120	0
Biofuel	43.7//43.2	0//0.263
E-Fuel	42.8	0.263

Table 2.3 – Energy Content and CO2e released per Kilogram.

Biofuel has two values as the first is the energy content and CO2 released in the Fischer-tropsch method and the second is the alcohol-to-jet produced biofuel.

2.1.4 Supply Sector

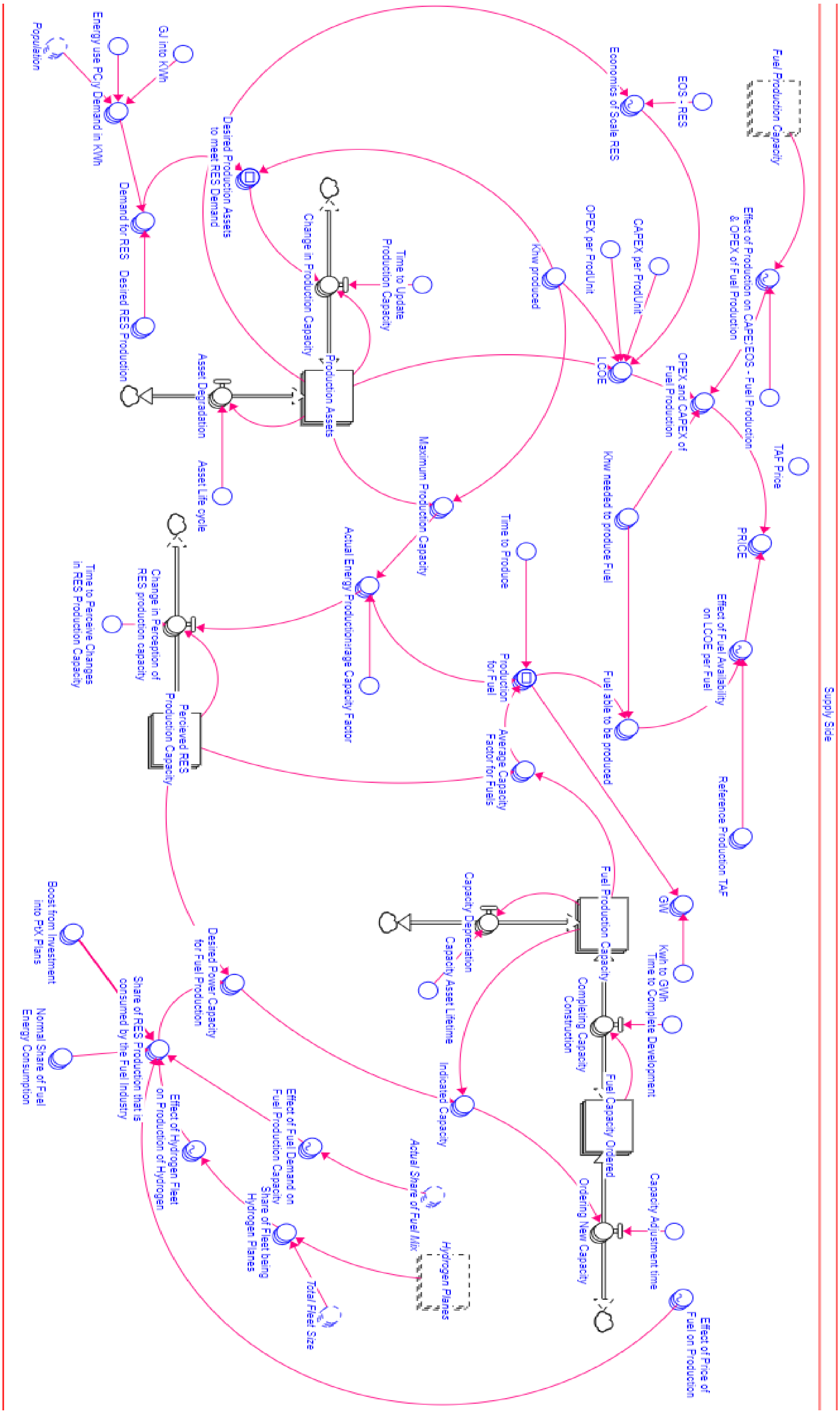

Figure 2.6 – Supply Side Sector

Demand relies on supply, as if there is no supply the demand will eventually dwindle out unless there is a sign of production. This aggregated and much simplified sector takes input from data from the countries regarding their share of energy production derived from renewable energy sources (RES). The share of energy production from RES determines the production of sustainable aviation fuel as it would not be sustainable if the fuels were produced from high emission substances. The RES energy production affects the fuel production structure capacity measured in kWh (kilo-watt hours) which is loosely based on the price-structure from Sterman (2010).

The fuel capacity is driven by a share of RES energy production that is used by the fuel production sector. The assumption being that there is no energy nor fuel imports. Realistically, there is a lot of trading between the three countries, so there is less incentive for each individual nation to construct their own fuel production facilities (MPE 2023). The trading of fuel and energy was omitted due to the complexity of the structure and model boundary.

The fuel capacity is the energy that can be used for fuel production. Fuel capacity is often measured in energy terms such as MW, and GW (Brintbranchen 2022). Having a 4 MW capacity of hydrogen production is the energy able to be produced when the electrolyser (or any other production asset) is running at full blast (ONE 2023). It is rare to have production be at max capacity for extended periods of times, hence the capacity utilization (Pearlson et al. 2013). Yet, the model does not include such a variable due to its simplified nature. It is therefore, assumed that the fuel production capacity could either be always running with full utilization or which is more realistic, the utilization is affecting the fuel production but is simply not in the model. Therefore, the stock of fuel production capacity accounts for utilization without it being present.

The fuel production capacity is measured in kWh, the model then converts that capacity production into the fuel by using the energy (in kWh) used per kg of fuel. It is assumed that the production capacity is fully used every year, hence being measured in kWh, instead of stating that there is 12 GW capacity, the time measurement shows the energy used per time unit. *Table 2.4* shows the kWh needed per fuel based on today’s calculations (FCHJU 2014; Hillestad et al. 2018; Trinh 2021; Hao et al. 2021).

Fuel	*kWh used in the production*
Traditional Aviation Fuel	0
Hydrogen	53
Biofuel	15.16
E-Fuel	10

Table 2.4 – kWh needed in Fuel Production

The kWh used in the production of TAF is 0 as the supply side is not concerned with oil-based fuel as it is assumed to have an infinite supply and always be available. Realistically that assumption may not hold looking 20 or 30 years into the future but in interest of condensing the model this assumption will remain. The inclusion of feedstock and more in-depth supply lines would be beneficial and interesting research.

2.1.5 Fuel Attractiveness Sector

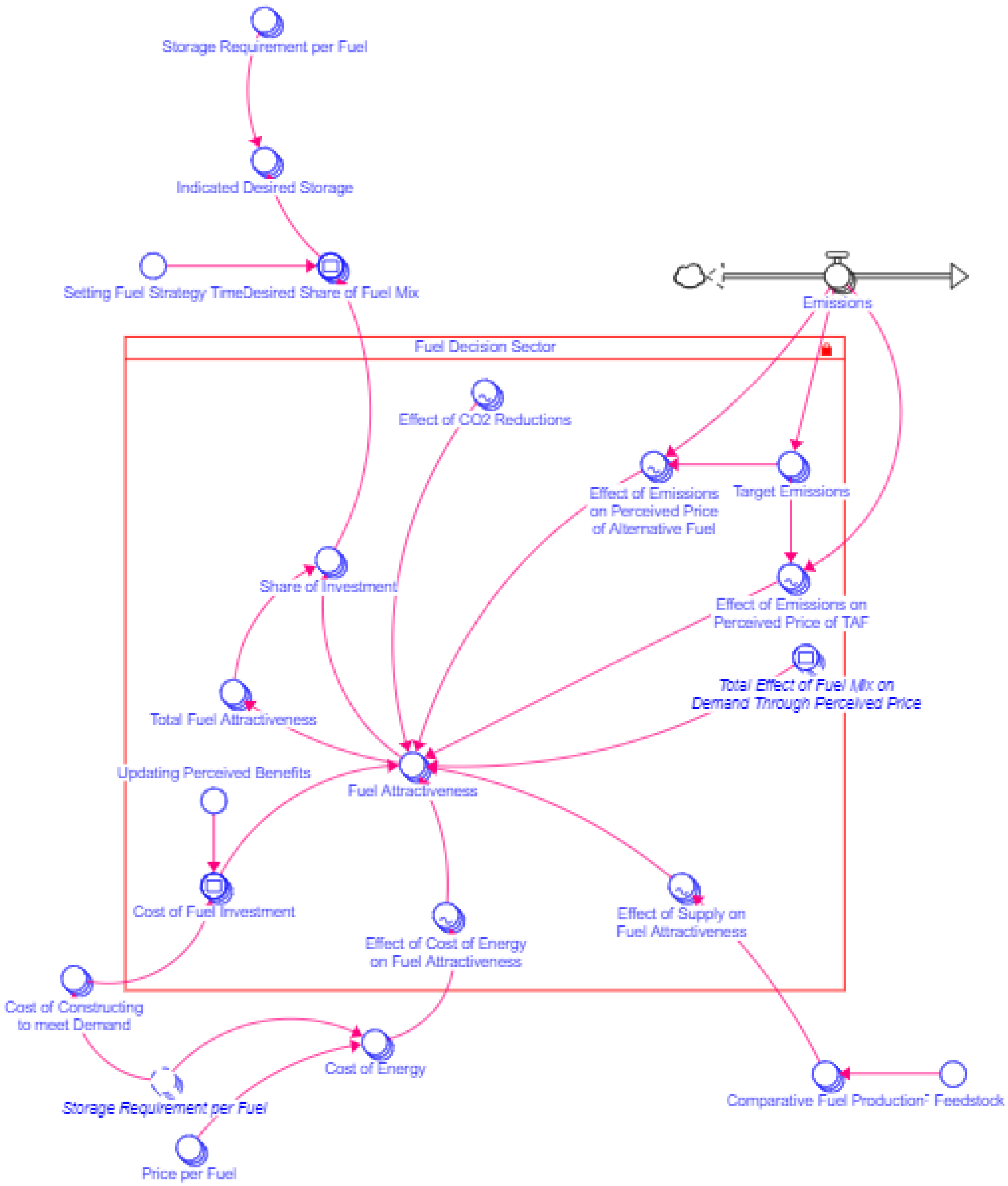

Figure 2.7 – Fuel Attractiveness Sector

Every transition is a collection of comparison and decisions. This sector aims to simplify the complexity of these transitions into an easy to communicate structure (Markard et al. 2012; Barlas 2007). The sector is heavily inspired by the system maps of Gursan and De Gooyert (2020), although it is a non-simulation model, the structural concepts were applied in similar manners in this decision sector (Gursan and De Gooyert 2020). The inputs into the decisions are the gap between current and target emissions, supply, price per kg of fuel, the cost of constructing new infrastructure, and the effect of transition onto perceived price (i.e., the reaction of the public to the perceived price).

The price of fuel is a main driver in the model as there will be no transition unless the price per kg of fuel decreases. A reason, besides availability, that the transition is occurring so slowly is the cost of the new alternative fuels as current costs are at least thrice as expensive (Ajanovic et al. 2022; Enevolden et al. 2014; Ghaebi Panah et al. 2022; Franke 2021). The structure of the model is thus set up as a comparison between the price of the fuel and the price of TAF which is based on Jet A-1. This is to represent the comparison that the executive would be making mentally to see whether it makes economic sense to transition.

The jet A-1 price is exogenous data from the year 1980 to 2022, after which the price is kept at the 2022 level. *Figure 2.8* shows the price and behaviour after the data ends. The decision to keep the price constant is due to the high fluctuations in the market (IATA 2023). It would not make sense to use the general trend of the price as it fluctuates constantly (IATA 2023). Hence, assuming the fluctuations continue, the assumption is that the average price will remain around the same 2022 level and therefore, for simplicity's sake will be kept constant at the 2022 level.

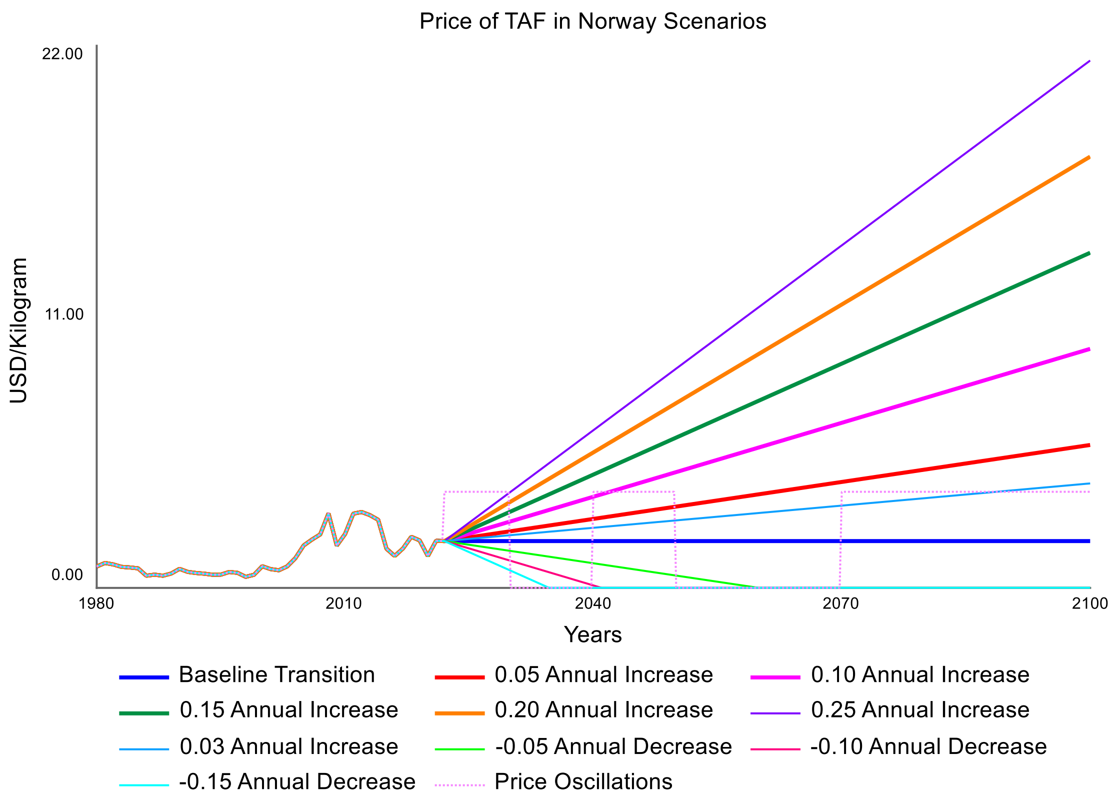

Figure 2.8 – Simulations for TAF

The annual increase runs, and the annual decrease runs are meant to represent scenarios where the price starts to increase or decrease by the specific values annually. This has the expected effect of either accelerating the transition when the price increases and deaccelerating when the price decreases towards 0 as it is impossibly cheap. The sensitivity of this variable is explored further in section 2.2: Sensitivity Analysis and Appendix B: Sensitivity Analysis.

The equation for fuel attractiveness is given below. It has three components which are the cost it would take to construct all the new infrastructure per fuel, the cost it would take to meet the full demand with one specific fuel, and the climate benefits.

$$Fuel\ Attractiveness = (Cost\ of\ Infrastructure * Availability) * (Cost\ of\ Fuel * Effect\ of\ Perceived\ price) * (Effect\ of\ Emission\ Targets * Effect\ of\ CO2\ LCA\ Reduction)$$

The availability controls the variable as if there is no supply of the fuel the whole variable is 0. The emission component is intended to show that despite the cost of the fuel being higher than TAF there are more benefits that need to be considered. The last component is the price of fuel as it is a major aspect of the decision to transition.

The fuel attractiveness is then summed up per country and fractionalized towards itself in the following equation:

$$Share\ of\ Investment\ per\ Fuel = \frac{Fuel\ Attractivness\ per\ Fuel}{Total\ Fuel\ Attractivenes}$$

Thus, the larger the attractiveness the more investment the airports will allow into the specific fuel. This then drives the desired share of fuel which gives strength to the infrastructure sector to either continue or start construction.

2.1.6 Infrastructure Sector

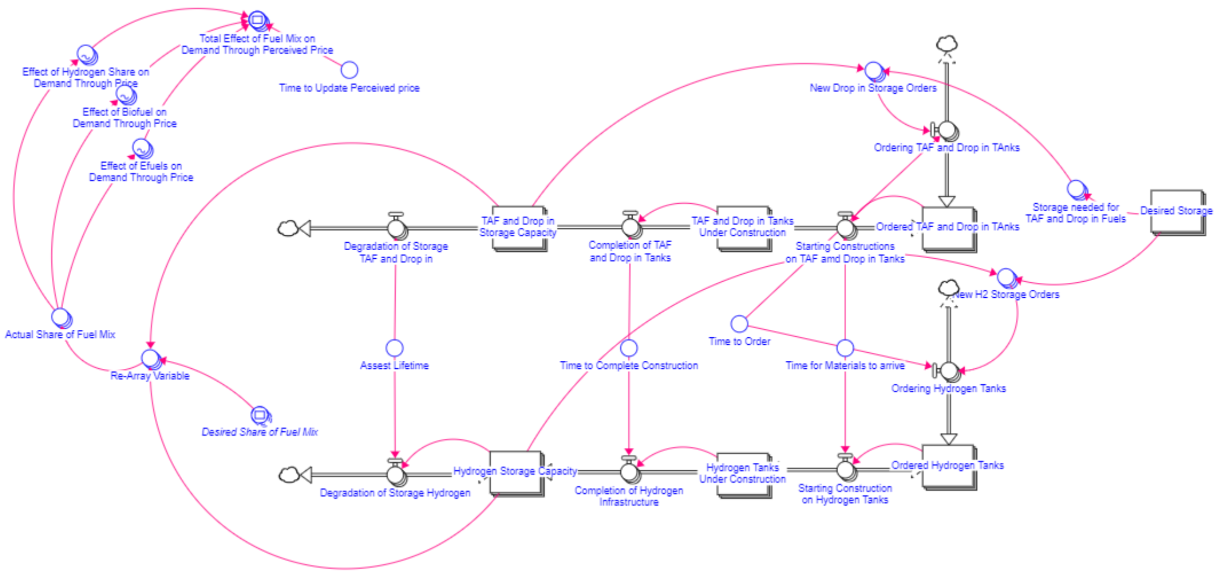

Figure 2.9 – Infrastructure Sector

Lastly, the infrastructure sector consists of two material delays for hydrogen storage and drop-in fuel storage. Delays present in the system cause the infrastructure to slowly increase representing the time to close the gap of desired and actual share of fuel mix. Data regarding infrastructure costs, times, and lifetimes are elusive and thus, all parameters are based on reasoning and calibration.

The costs of switching to alternative fuels need to be recouped from somewhere and more times than not, it becomes the customers job to do so (Davis and Hausman 2022). Thus, the last connection is the perceived price of ticket which is a function of the actual share of SAF in the fuel mix. The transitional cost will eventually be found in the ticket price which results in more expensive tickets which has an effect on demand and is a part of the consideration whether to transition or not.

2.2 Sensitivity & Validation

The validation tests constructed by Barlas (1996), Sterman (2010), and Senge & Forrester (1980) intend to see whether the model generates the "…the right output behaviour for the right reasons" (Barlas 1996, p186). The tests examine the dimensional, behavioural, and structural aspects of the model through changing parameters, testing assumptions, and exhausting the model (Sterman 2010). The usefulness of the model is based on how confident one can be in its purpose as a tool (Senge & Forrester 1980). To build confidence in the structure these tests are necessary as they demonstrate the robustness and realistic behaviour, within the boundaries of the model.

2.2.1 Dimensional Consistency

The dimension of a model refers to the units of the variables. Unit errors are the results of the dimensions not being formulated correctly and logically. On the surface level, dimensional consistency is simply asking whether the capital variables have a currency as a unit or whether the stock of workers has a 'person' label. The 'big picture' of dimensional consistency is whether the model and its equation synchronise to have all the units match. The presence of unit errors often means missing structures or incorrectly formulated equations. The SD model constructed contains no unit errors and is dimensionally realistic and consistent.

2.2.2 Integration Validation

Integration validation is the testing of the integration method of the model and is meant to ensure that simulation parameters and the integration method do not greatly affect the model behaviour (Sterman 2010; Schwaninger & Grösser 2020). The following simulation parameters were used for the simulation:

Parameter	*Value*
Start Time	1980
Stop Time	2100
DT	1/4
Integration Method	Euler

Table 2.5 – Simulation Parameters

The stop time, DT, integration method is not sensitive to any changes. The model behaves logically under all conditions, be that doubling the stop time, changing the DT, or switching the integration method. The only sensitive aspect of the integration is the start time as the exogenous data used to drive aspects of the model only contain data from the 1980s onwards. Thus, an early, not a later, start time affects parameters as they are extrapolated to match the 1980s value.

2.2.3 Extreme Condition Testing

There are two types of extreme condition testing: direct and indirect extreme testing. The question that the modeller is asking during these tests is "Does the model respond plausibly when subjected to extreme policies, shocks, and parameters?" (Sterman 2010, p860). The direct test is whether each singular equation or structure simulates plausible response to extreme tests. Indirect extreme testing assesses the response from the complete model structure.

Both tests were conducted on the structure and the direct extreme testing showed a few variables that were unrobust to the scenarios, this was remedied through the use of MIN and MAX function to put plausible limits to the system (fuel mix cannot go below 0 as an example). Using MIN and MAX function does not create an undynamic model, it simply places limits on the behaviour that should not be occurring. These limits exist in natural systems as well and could be endogenously included but that could result in a model that is larger, and less well made. System dynamics aims to simplify and communicate complex systems so constructing unnecessarily large models muddy the insights and the ability to communicate them to others.

The indirect testing was performed under several scenarios as shown in *Table 2.6* and in *Figure 2.10*. The model was robust in most scenarios, the few scenarios where it behaved oddly are fringe impossible scenarios (negative demand, and no reconstruction after earthquake). Realistically, demand cannot go negative nor if an earthquake occurs will there be no reconstruction, so the model still upholds its robustness within plausible scenarios. The model being valid means it needs to behave plausibly and expectedly to these extreme shocks but there certainly is an argument for the model not being required to be plausible in all scenarios as long as those are not detrimental to the purpose or scenarios that statistically are unlikely but still possible (Sterman 2010). Thus, as the model did not break it is still valid and upholds in most extreme scenarios. This, however, does lead to more uncertainty but overall, as long as the reason for the odd behaviour can be explained it is not yet useless.

The infrastructure becomes positive in the late 90s as the equation for ordering new infrastructure is:

$$Ordering = Desired\ Storage - Current\ Storage$$

If the current storage is larger than the desired storage (even when negative) the ordering becomes positive. The current storage becomes larger than the desired as the outflow has a delay of 35 years, so it will still 'drain' but since it is negative it will increase the stock and thus become larger than desired. Regarding, the 'earthquake with no reconstruction' scenario, even if the stock is emptied and the inflow is switched off the stock will not reach 0 but become insignificantly small but never 0, so technically the actual fuel mix is never 0 hence, the equations still showing SAF become part of the fuel mix.

Scenario	Variables & Values	Expected Behaviour	Simulated Behaviour
No Renewable Energy Sources	Demand for RES = 0	The emissions and air travel demand grows exponentially but since there is no RES production there cannot be any SAF and thus, no transition.	Matches the expected behaviour.
No Storage and Negative Storage	Drop-in Storage = 0 and -1e12	If the storage is 0 then there should be a large jump early in the simulation to meet the fuel demand and then behave normally. If it is set to -1e12 it should cause a jump from 0 in the fuel to 1 almost instantly the model will start to construct storage	Matches expected behaviour.
No Travel Demand and Negative Demand	Air Travel Demand = *0 and -1e6	As there is no airport demand, structure declines since there is no need to construct anymore. The supply side still works but there is no transition as there is zero fuel demand for all fuels. If the demand is negative the same behaviour will occur.	Matches expected behaviour when demand is 0 but not for negative demand. The infrastructure starts out negative but slowly increases towards a positive value.
Sudden Increase in Energy Demand	Total Civil Aviation Demand = STEP(1e12, 2040)	There should be a jump in emissions, but the transition should not be affected in a major way as the infrastructure will increase in proportion to demand.	Matches expected behaviour in emissions but the transition is slightly different but not unrealistically so.
Earthquake destroying all infrastructure in 2040 with no rebuilding	Outflow for both storage stocks = STEP(Stock, 2040) Inflow to stocks = (1-STEP(1, 2040).	Actual fuel mix should go to 0, emissions will continue to grow as the model assumes that scenarios as such will never occur.	The actual share of fuel mix does not go to 0 despite both the numerator and denominator being 0.

Table 2.6 – Extreme Condition Testing Overview

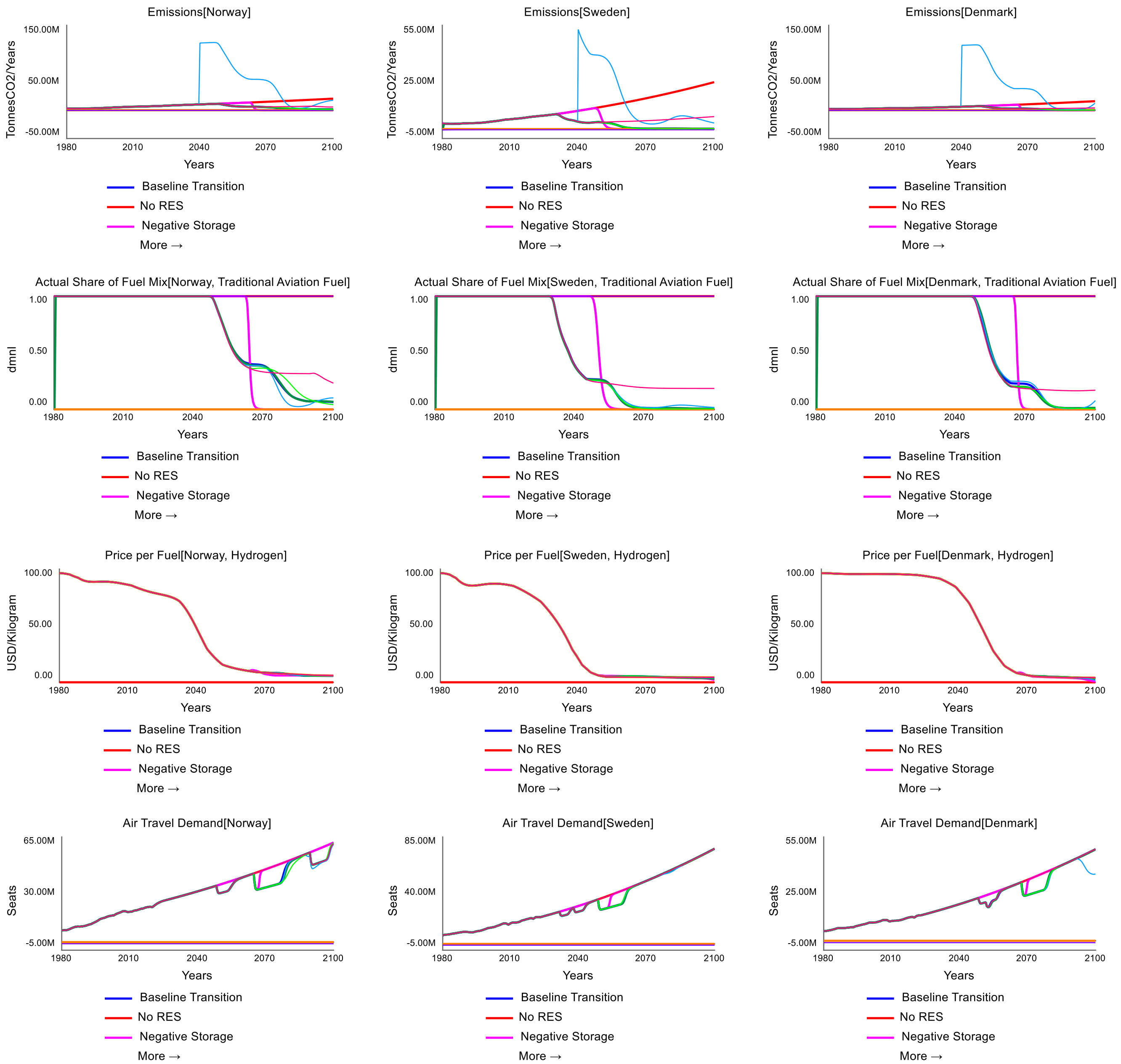

Figure 2. 10 – Overview of Extreme Condition Testing Results

2.2.4 Sensitivity Analysis

A sensitivity analysis aims to reveal variation in output with variation in input, in other words it highlights the simulation space that the model operates within. Finding parameters, that are sensitive will indicate where intervention or possible policies can be implemented. There are three types of sensitivity: 1) numerical sensitivity – a change in a parameter either strengthens or weakens the behaviour mode of the model, so if it is showing exponential growth then the exponential growth would either be stronger or weaker. 2) behavioural sensitivity – a change in parameters causes a switch of the behaviour mode such as a transition from exponential growth to oscillations. And 3) policy sensitivity – where changing assumptions under policies lead to different, unintended effects (Sterman 2010, p883). All models are numerically sensitive and thus, will not be covered unless relevant. So, exploring the simulation space leads to an understanding of what 'can be done about it'. In this section, the results of that analysis will be summarized and discussed, for a more in depth view see appendix B: Sensitivity Analysis.

Overview of Sensitivity

The model was mainly sensitive numerically meaning only a few of the changes (mainly assumptions) would cause changes in behavioural modes. In all cases (unless extreme) a transition occurs eventually. The main difference was the speed, timing, and which fuel dominated the market share. The last difference not being relevant unless the characteristics/parameters related to the fuel were involved. The speed and timing of the transition was mainly numerically sensitive to adjustment times, i.e., if the inherent delays in the system are less, the transition occurs faster. This is not unique as less delays would evidently make the transition occur faster. The interesting aspect of this is that collaboration, and more efficient supply chain could aid in transitioning but nevertheless, that is outside the scope of the model but is a discussion point in chapter 4.

The key insight from the sensitivity is related to the assumptions, which are the exogenously driven extrapolation, of traditional aviation fuel price, share of energy production that is from renewable energy sources, and share of energy intended per fuel etc. The main drivers of transition are supply, costs of infrastructure transition, emission targets, and most importantly, price. Thus, different assumptions of price will lead to different behaviours. Increase in price (after the end of the data) would cause an earlier transition as economically it would be cheaper to transition earlier. If the price decreases, eventually becoming 0, the transition would not occur or rebound back as the fuel purchase (direction operating costs) is the majority of costs for airlines and airports (ICAO 2017). So, if they can save those costs then regardless of the benefits of the other fuels it does not make financial sense. *Figure 2.11* shows the simulation space for share of fuel mix consisting of TAF for Sweden based on variations in the TAF price as all countries display similar behaviour.

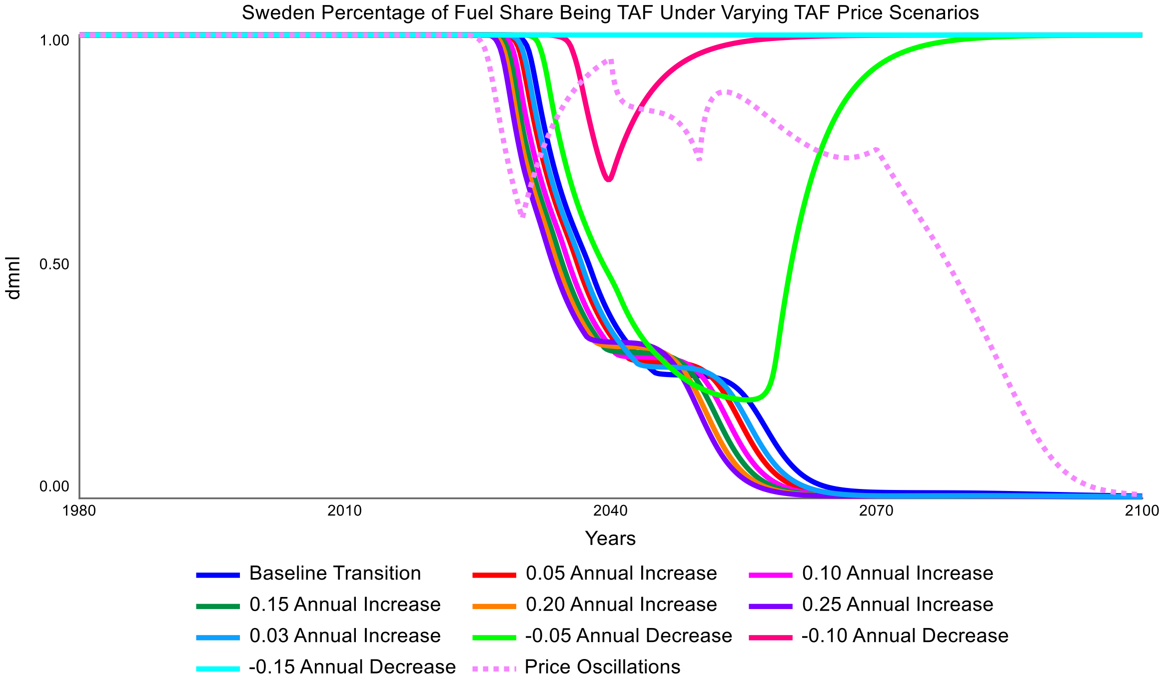

Figure 2.11 – Sensitivity for TAF price and its effect on Share of Fuel mix being TAF in Sweden

This uncertainty derived from crucial drivers in the model seemingly damages the model's validity. However, the behaviour mode remains the same in all but three cases, specifically, -0.05, -0.10, and -0.15 and in those cases the price goes to 0 a few years prior to the infliction point. This indicates that the only price scenario that stops transitions is when traditional high emission fuel becomes free, which would be a dream for companies but considering the production costs it will remain an unrealistic dream. If the only cases that stop the transition are impossible, the uncertainty from those situations inherit that impossibility as well.

Chapter 3: Simulation Results

In this section the simulation results will be presented under different scenarios. There will be four scenarios presented and their effects will be highlighted through the key performance indicators (KPIs) emissions and share of fuel mix. Each country is highlighted prior to the full comparison of results and then in the next section the transitions in general are discussed. The first one is the business as usual (BAU) scenario, which is the base assumption case and the comparison reference for the other scenarios. The assumptions being that the emission targets aim to be carbon neutral by 2050, hydrogen has a larger initial share of production, price for TAF is stagnant after 2022, and there are PtX plans in place for all the countries.

The second scenario contains no PtX plans and no emissions targets to see whether the 'free market' can support itself. The third scenario are policy focused simulations to see where the policy interventions can occur and whether those policies are likely to be implemented. The fourth scenario targets the supply side of the model to see how variation in availability and production affects the outcome.

3.1 Sweden

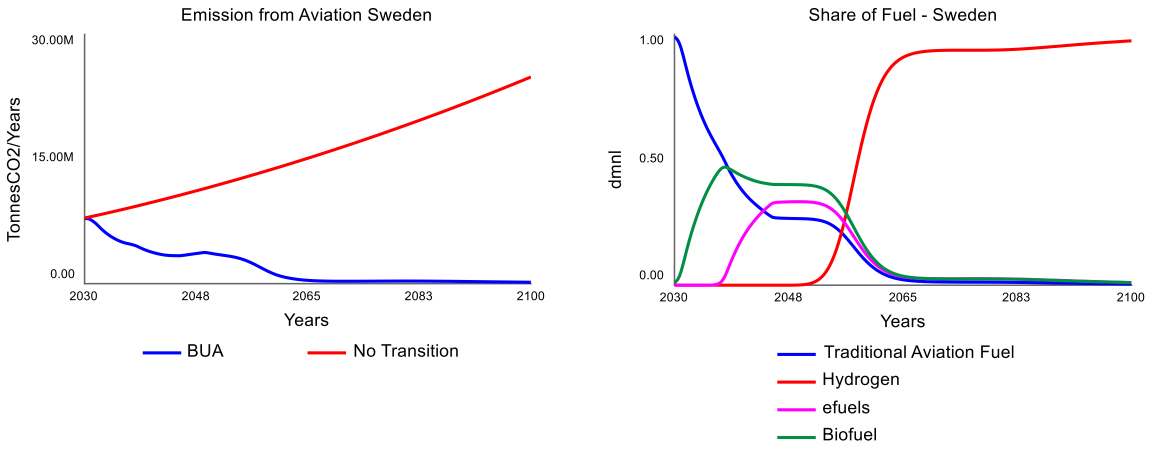

Figure 3.1 – BUA scenario for Sweden between 2030 and 2100

Sweden starts transitioning to drop-in fuels in the year 2030 and as expected it is initially biofuel due to its relative 'easier' production and availability. There initially is a sharp decline of TAF down to 53% of the fuel share over a 7 year period. In the same year that TAF reaches 53% e-fuels start to be adopted as well. Biofuel still has a controlling share of 40% in the year 2044 where the growth of the drop-in fuels as well as the decline of TAF stagnates. This stems from the fact that hydrogen is starting to enter the region where it is affordable enough with a sufficient supply to consider the cost of transitioning. So, the attractiveness of the other fuel languishes as hydrogen slowly enters the market in 2050 and over the span of 14 years (2050-2064) gains a controlling 91% share of demand. It does not reach the 100% mark as there is still some attractiveness remaining for the other non-TAF fuels. Important to note is that the TAF is not 0, indicating that there seems to be some reason to hold off from a full transition. However, that seems to be a model specific behaviour as if hydrogen and drop-in fuels control 98% of demand then in reality it would probably consist of 100% of demand as 2% is not a lot to hold out for. Interestingly, liquid hydrogen does decrease the rate of its adoption after reaching 90% and then only gradually increases towards a full market share.

Emissions start to decline in 2030 in synchroneity with the adoption of biofuel, yet it does not reach 0 before 2100 as biofuel and TAF are still in demand. However, if there is no transition the emission in 2100 would be 24 million tonnes of CO2 annually, so the 168k tonnes that are being released in the simulation is relatively satisfactory when compared to the alternative. The 168k tonnes could be offset and be reduced in a full transition to hydrogen as there is no CO2 release from it.

3.2 Norway

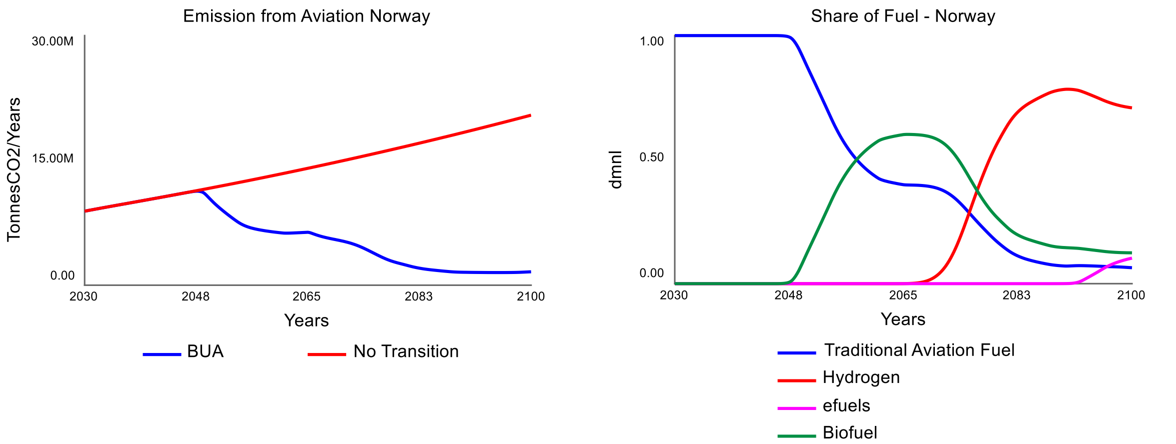

Figure 3.2 – BUA scenario for Norway between 2030 and 2100

The transition does not start in Norway until 2048, when biofuel increases decreasingly to 60% of the fuel share in 2064 before stagnating until 2066 where it starts to decline as liquid hydrogen becomes introduced. As hydrogen has a higher energy content and less CO2 emissions per kg of fuel it quickly becomes a dominant fuel in the market and by 2088 80% of fuel demand is liquid hydrogen. There is an infliction point in hydrogen demand in 2090 where the demand starts to decline as e-fuels become introduced into the market noticeably removing hydrogen demand and not TAF and biofuel. The relatively late introduction of e-fuels is due to the dominant characteristics of hydrogen. *Figure 3.2* displays the simulation time 2030 to 2100 and at the later time in the simulation it seems like hydrogen is declining, it is not. The model was simulated to 2500 to see if hydrogen is declining or simply oscillating. It is oscillating in sync with e-fuels in a general positive trend. So, over time the oscillations increase towards 100% of the fuel share.

The emissions are reduced by a substantial 19 million tonnes of CO2 compared to the no transition scenario. There is still an annual release of 1.6 million tonnes due to biofuel and TAF being 12% and 6% of the fuel share respectively in the year 2100.

3.3 Denmark

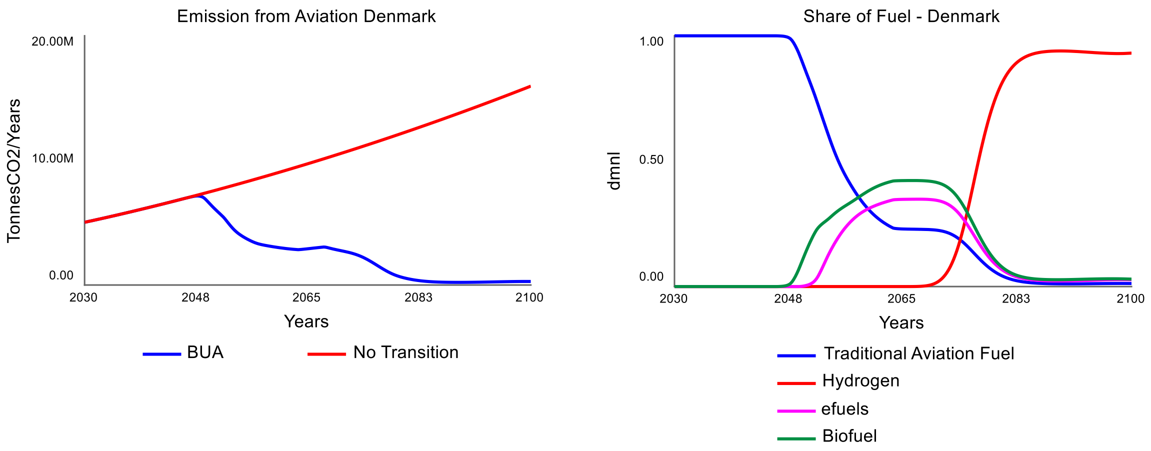

Figure 3.3 – BUA scenario for Denmark between 2030 and 2100

Denmark has a relative late transition to SAF where the two drop-in fuels (biofuel and e-fuels) do not become adopted until 2048 and 2050 respectively. They both achieve the highest share in 2063 where the demand consists of 42% biofuel and 35% e-fuels. That split remains until 2069 following the adoption of liquid hydrogen (hydrogen fuels) to the market. Hydrogen then rapidly takes over until 2083 where the growth of hydrogen stagnates and then declines gradually. Looking past the shown simulation time of 2100 it does recuperate and becomes effectively 100% of the fuel share after 2100.

Emissions decline once biofuel becomes part of the fuel share and reach their lowest value of 213k tonnes of CO2 in 2083 after which it starts to increase again. This stems from the biofuel still being part of the fuel share as biofuel is not fully carbon neutral. So, if 1% of the fuel is biofuel and the demand increases, emissions will increase as well as the 1% of biofuel becomes larger but stays the same in terms of relativeness to the entire fuel share and thus, continues to emit CO2e.

3.4 Loop Explanation & Comparisons

As the model is arrayed by the different countries, the structure is the same for all three countries and thus, the loop interactions are the same. It is therefore that the behavioural explanation will cover a general transition within the countries and not each individual nation.

3.4.1 Behavioural Explanation through Loops

Prior to the transition the lock in mechanism (R1) is strong as transitioning to the SAFs is expensive (mainly hydrogen as the other fuels can be dropped-in) and the benefits such as cheap fuel, and lower emissions are not yet worth the transition. The transition only begins once the price has become within a range around the price of TAF where even if the specific fuel is more expensive, the benefits make it more attractive than the cheaper TAF. Once the production is large enough to put the price of fuel within that range, the balancing price to supply loop (B5) starts for biofuel as it slowly becomes part of the share. The delay in constructing additional storage is ignored with biofuel as they can use the pre-existing fuel tanks. B5 decreases the price while being mildly counteracted by the balancing price to demand (B4) loop. However, the demand can only increase it slightly, so the fuel is still more attractive than TAF. The switch to biofuel causes the balancing emission to fuel usage loop to activate and start to balance the emissions towards the new low carbon fuel.

Once e-fuels enter the price range its B4 and B5 loops start and the balancing price to fuel loop (B3) has a lot of strength due to not yet meeting climate targets e-fuels start to gain traction as well as they emit less CO2e per kg. The fuels are constantly competing for attractiveness so while the e-fuel loops are becoming stronger, so are the hydrogen loops. So, once hydrogen enters the 'acceptable' price range the strength of the R1 loop that is currently locked into drop-in fuels stops it from transitioning. This means that until hydrogen is below the price of TAF it will not transition. This is in contrast to drop-in fuels as they only need to be within a certain range due to the lack of need to switch infrastructure. So once hydrogen is attractive the airports start to order new construction for hydrogen storage tanks resulting in an increase in strength of hydrogens B2, B5, R2, and B3 at the cost of decreasing the dominant position of R1 for drop-in fuels. However, as the other fuels' loops still have strength, and the characteristics of each fuel are still making them attractive, thus, the hydrogen dimension does not take full control over the system yet and instead enters a gradual increase as the strength of the other fuels counteracts hydrogen.

3.4.2 BAU Comparison

Despite the similar trajectory and 'shape' of the transition in the three countries, there are differences that reflect the unique obstacles each country will need to overcome. Sweden is the earliest to transition as they reach the desired alternative fuel production capacity the earliest. This occurs in the year 2030 while the other countries do not start adopting until the late the 2040s. The structural reason for this is that Sweden has a larger energy production due to its population being larger and therefore can increase its alternative fuel production capacity much quicker. So, despite having the largest demand of flights and a lower RES production, Sweden manages to transition due to its pre-existing renewable energy production. Realistically, Norway produces the most energy as they have become the energy powerhouse of the north, especially renewable energy (Nordic Statistics Database 2022). Additionally, Norway mainly produces green energy through hydro and wind (Nordic Statistics Database 2022), this raises the question of whether the simulation results reflect the actual real life scenario. The reason that Sweden outcompetes Norway despite its staggering potential is a geographically induced one. For all the beautiful scenery that the fjords provide, it does make it difficult to set up fuel supply lines that do not emit CO2e (DNV 2022b). Considering the methods of transport (maritime, road, or grid) need to be converted as well before aviation can begin to reduce its emissions, the obstacles are larger. The other solution is then to build the production plants locally but that takes time and investments, and due to Norway's size, it would mean a large amount of production plants are required (DNV 2022b).

In comparison, Denmark is relatively flat, small, and has only a few airport hubs (Copenhagen, Billund, and Aarhus) meaning the connective network can be 1) smaller in size, 2) easier to connect, and 3) without needing the production plants nearby as the transportation of the fuel does not need to 'cross mountains' to be used. However, despite the advances laid out earlier, Denmark is still slow in transitioning as they are the slowest to increase their fuel capacity to a comparative level of traditional jet fuel. Therefore, the attractiveness of TAF remains high until 2048 where the transition occurs. Additionally, Denmark has placed high priority on the implementation of PtX and PtL plans that will boost hydrogen systems and distribution hubs that greatly increase the effectiveness and speed of the transition (ENS 2021).

Sweden and Norway are also investing into PtL production but have comparatively fallen behind on that endeavour. Norway is building its first PtL plant to be finished in 2024 but due to the location (Mosjoen) there is opposition against it (Norsk E-fuel 2022; Stai 2023). Sweden has recently started construction on the first PtL plant as well but will not deliver its first batch of SAF until 2025 (Genemo 2022). It is important to note that both cases only discuss capacity to produce and not general acceptance from the market. In Norway's case the plant is in partnership with Norwegian so there one can assume that there is demand but no such statements were found for the Swedish case.

In contrast, Denmark has created a partnership and government supported plans to construct a country wide PtX system that should create 12 GW capacity for hydrogen production by 2030 (ENS 2022). The plans are still to only start producing by 2024-2025 depending on the company but there is more, for a lack of a better term, excitement revolving the projects compared to the other countries.

So, despite seemingly having the most potential for SAF, in terms of infrastructure and cooperation, why is Denmark not the first to start using SAF? Assuming the model is correct in its prediction there can be a plethora of reasons for the discrepancy. A key reason is the financial aspect of it, where the insufficient production means the price of SAF remains high and a high price keeps demand low, a chicken-or-the-egg conundrum (NTRANs 2021). Thus, if the production is increasing too slowly the price will not enter the 'acceptable' range and thus, no transition occurs, or it occurs at a later date. Sustainable transitions are complex processes and cannot be reduced to one problem so, the economic aspect is not the only reason why Denmark is slow in transitioning comparatively. An additional issue within Demark is the previously praised partnership, as it is more fluid than a tight community and disagreements arise consistently (Andreasen & Sovacool 2014). Andreasen & Sovacool (2014, p896) state in their research into hydrogen stakeholders that "stakeholder agreement on energy issues—given their political nature, given the variety of separate pathways that exist for producing low-carbon energy—will perhaps always remain ephemeral…. Consensus, whenever it exists, is fleeting and fragile, and so researchers ought to prepare themselves for less of it, rather than more."

Consensus and agreements are not just a Danish problem but a general problem within any sector needing to transition, but generalizing this between the Scandinavian countries it may be the case that due to Denmark's smaller size and effectively only having one large airport (in Copenhagen) more disagreements arise as there is only one access point to the market (Wormslev 2016). In Norway, the geographical challenges mean there is a large distribution of airports so there are more access points to the markets which makes it easier to enter as you do not have to construct the plants only in Oslo, as an example (Wormslev 2016). Similarly, Sweden also contains multiple major airport hubs, thus having easier access to demand and therefore, larger incentive to construct with less infighting between production partners.

Returning to the result, there exists agreement in the literature and other reports regarding the order of transition: first biofuel, then e-fuel, and lastly liquid hydrogen (Ydersbond et al. 2022; Mortensen et al. 2019; Kristensen et al. 2021; ICAO 2022). The difference lies in the timing of the transitions. The literature agrees that SAF will start to be adopted around 2025-2030 slowly but gradually, this scenario is becoming more likely as the EU and national governments are considering regulations that enforce a certain share of fuel usage be SAF by certain years (EP 2021b). The model does not consider ‘forcing’ regulations only government support when the emission targets are off, so that could be a reason for the discrepancy. However, there is certainly an argument for a middle ground where the introduction of feedback means that the predicted transitions occur later but not as late as 2048 in the case of Norway and Denmark. Business and governments have a tendency to propose optimistic timelines as they need to please stakeholders and investors, therefore, the predictions should always be viewed from a critical perspective (Uscbasaran et al. 2010). As the reader should also do with the timeline derived from the simulated scenarios. Yet, the important insights from the model are the obstacles and feedback loops that exist rather than the exact timing, as no one can predict the exact timeline of SAF demand, every report or forecast is trying to display their mental model based on the data presented and the novelty of using system dynamics to do so is no different. The use of system dynamics simply communicates that there is more complexity and feedback which can result in further delays and then highlights those mechanisms. The communication of these mechanisms is the key insight of the results.

To summarize, sustainable transitions are not simple processes and thus, contain many obstacles from different aspects. There are geographical, economic, social, technical, and logistical obstacles that give way to divergence between Denmark, Norway, and Sweden. The results presented seem to indicate that despite the latent potential of SAF in Denmark, it is the slowest to transition while Sweden starts the transition in 2030, 18 years earlier than Norway or Denmark. The structural reason for this is that the renewable energy production is larger in Sweden due to its larger population and can therefore, produce more SAF and thus, the price becomes lower earlier in comparison to Norway and Denmark. Ultimately, in Denmark and Norway not having the fuels to enter the ‘acceptable’ price range until the late 2040s. This differs from other SAF predictions as there is a consensus of the transition occurring between 2025 and 2030. Thus, the introduction of feedback highlights the complexity of sustainable transitions and consequently, demonstrates the potentially misplaced optimism present in the industry.

3.5 Scenarios

This section assesses three scenarios that provide further insight into the structure. The first scenario is the deactivation of the PtX boost to production and government/company emission targets. The second scenario is a policy exploration where the leverage points are tested based on common policies to see the effect they potentially can have on the transition. The third scenario focuses on supply side policies and analyse the possible interventions.

3.5.1 No PtX Plan and No Emission Target

In this scenario the boost from PtX or PtL plans is set to 1 and the emission targets are set equal to emission which makes the attractiveness of fuels based on emission targets equal to 1, and anything multiplied by 1 has no effect (effectively switching off the two sectors). It is meant to represent a scenario in which the government does not enforce any emission targets nor is supportive of any green infrastructure plans. It is an unrealistic scenario, but it is meant to examine the importance of government support by only focusing on the economic aspect of the fuels, i.e., price and supply.

Figure 3.4 shows the model result and behaviour when there is no government support compared to the BUA scenario. Sweden still transitions around 2030, the switch to biofuel occurs only 2 years later than the BAU scenario but Denmark and Norway display vastly different behaviour. Norway only starts to adopt biofuel in 2050 and does not consider any other fuel for the simulation time (till 2100) while Denmark adopts biofuel and then e-fuels two years apart and then proceeds to seemingly keep the fuels in equilibrium around 42% of actual fuel usage.

The lack of PtX investment and incentives from the government to reduce its emissions cause the price of the fuel to take more of a central role in the transition. Since the environmental benefits are not accounted for the ‘acceptable’ price range of the fuel becomes less and thus, the fuel needs to become cheaper before it starts to become attractive. However, since there is no PtX plan in place the supply side is slower in increasing its fuel production capacity and thus, in the cases of Denmark and Norway, do not transition before 2100. Sweden due to its size, meets the reference Jet A1 production without the boost from PtX and emission targets which results in only a 2 year delay in transitioning. A simulation removing only the PtX plan was tested as well, and the results are almost identical compared to the no PtX and no emission target scenario indicating that the important part is the PtX plan rather than the combination. Despite, the lack of emission targets reducing the acceptable price range, if the supply side is not able to produce enough to substantially decrease the price there is no demand for it. So, in this scenario the chicken-and-the-egg conundrum of whether to first increase supply or to increase demand becomes front and centre as the lack of supply side policies reduces demand.

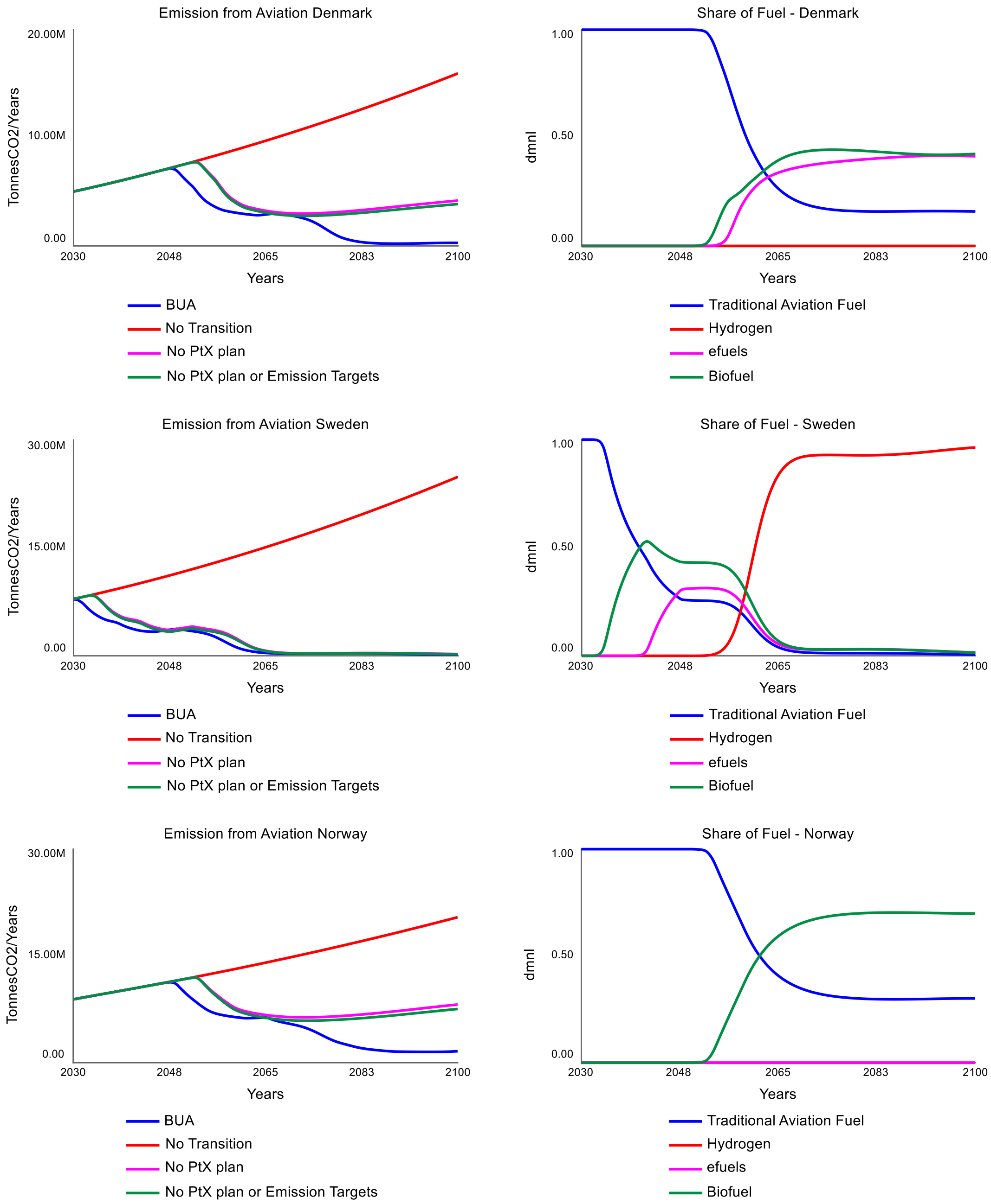

Figure 3.4 – No PtX plan or Emission Targets for all countries simulation between 2030 and 2100

This mostly affects liquid hydrogen as it is the most expensive of the fuels, hence, the lack of hydrogen usage in Denmark and Norway. This raises the question of whether in this scenario a transition to liquid hydrogen ever occurs. To examine that question the end time of the simulation was moved to see whether Denmark and Norway do eventually start to use hydrogen. *Figure 3.5* shows the result of that endeavour between the simulation years 2100 to 2200.

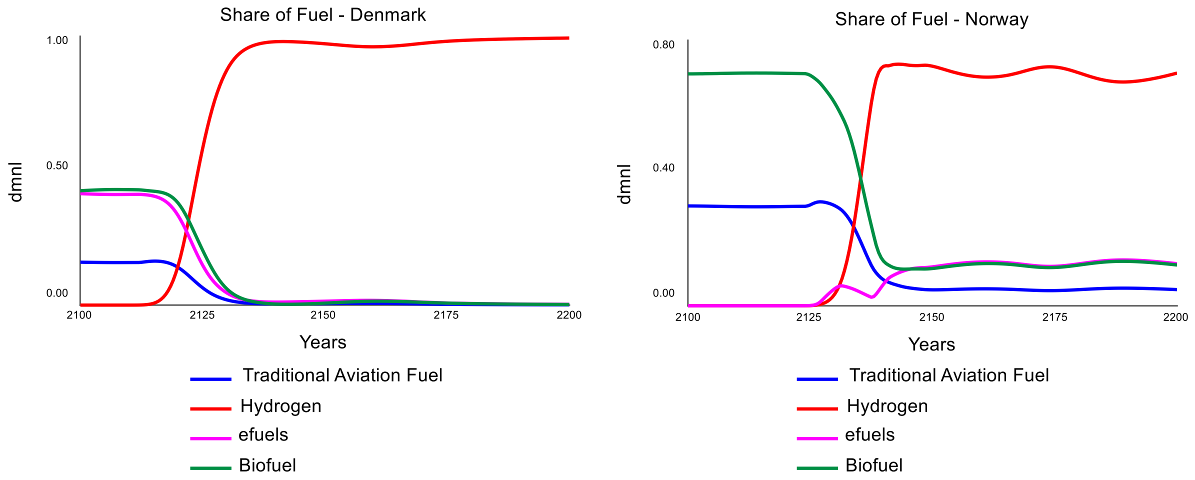

Figure 3.5 – Denmark and Norway in the No PtX and No emission Target Scenario from 2100 to 2200

Denmark switches to hydrogen and starts to use less of the other fuels (notably TAF) in the early 2110s while Norway does not start introducing e-fuel and hydrogen until the early 2120s. Structurally, Norway is the slowest to transition as without the boost to production through supply side policies, hydrogen and e-fuels do not reach the reference TAF production until 2118 and therefore, they do not transition as there simply is not enough production occurring within the country. Due to Norway's widely dispersed aviation network they produce a substantial amount of jet fuel (The Global Economy 2022c). This has locked Norway into that technology pathway and, structurally the R1 loop (locked in) is strong for drop-in fuels and the R2 loop is weak for e-fuels and hydrogen. Consequently, they do not become part of the share of fuel until late.

The key takeaway from this scenario is related to the role of supply side policies from the government. Demand will not be there unless price is decreased, and the way to artificially decrease price without subsidies is to implement policies that incentivize the producers to increase fuel production capacity. This further highlights the need for partnership and a holistic approach from both private and public organizations or institutions. Without regulators intervening, there is little economic sense, due to the high price of fuel, to transition until it is too late to substantially reduce climate change.

3.5.2 Policy Scenarios

Assessment of Measure with Regard to:	*SAF Blending Requirement*	*CO2e Reduction Requirement*	*SAF Fund*	*Fuel Tax*	*Passenger Tax*
Overall CO2e Reduction	YES	YES	YES	yes	yes
Flights Outside Scandinavia	YES	YES	YES	NO	YES
Reducing Demand	yes	yes	NO	YES	YES
Fuel Efficiency Operations	yes	yes	NO	YES	NO
Increased SAF	yes	YES	YES	yes	NO
Market Creation for SAF	yes	yes	YES	no	NO
Unintended Displacement of Operations	NO	NO	YES	yes	yes
Gov Budget Revenue	no	no	NO	yes	YES
Polluter-Pays-Principle	yes	YES	NO	YES	yes
Cost Effectiveness	NO	no	yes	YES	NO
Administrative Burden Minimized	no	NO	yes	no	yes

Table 3.1 – Five Policy Measures for Sustainable Aviation adapted from Ydersbond et al. (2020).

Sustainable transitions will require effect intervention from regulators and companies alike. In this section, two policies are tested to see their effects on the transition, both individually and combined. These policies stem from two aspects, the first policy is a fuel tax on TAF where the price of the TAF will be increased to make the other fuels more attractive as they are cheaper relative to TAF. This stems from Ydersbond et al. (2020), where several possible policies were conceptualized, and their effects summarized in *Table 3.1*, the stronger the colour the stronger the effect. Taxing the fuel would mean increasing the price of the tickets as the said tax will be passed on to the consumer (Ydersbond et al. 2020). However, that mechanism is not included in the model and therefore, only the fuel price will be increased by 50%. In real life the fuel tax would decrease the demand for flights resulting in a two-fold emission reduction.

The second policy is sourced from the price of infrastructure, specifically liquid hydrogen storage infrastructure. Due to the high cost of non-drop-in fuel storage, the transition to these fuels are considered to be vastly more expensive and thus, harder since there needs to be even more benefits to outweigh the cost. Thus, if the cost of infrastructure projects were reduced through subsidies, then the aviation industry may deem it more attractive and start to use it earlier than in the BUA case. Therefore, the second policy is an infrastructure subsidy that reduced the initial investment cost of 1kg of liquid hydrogen storage by 50%.

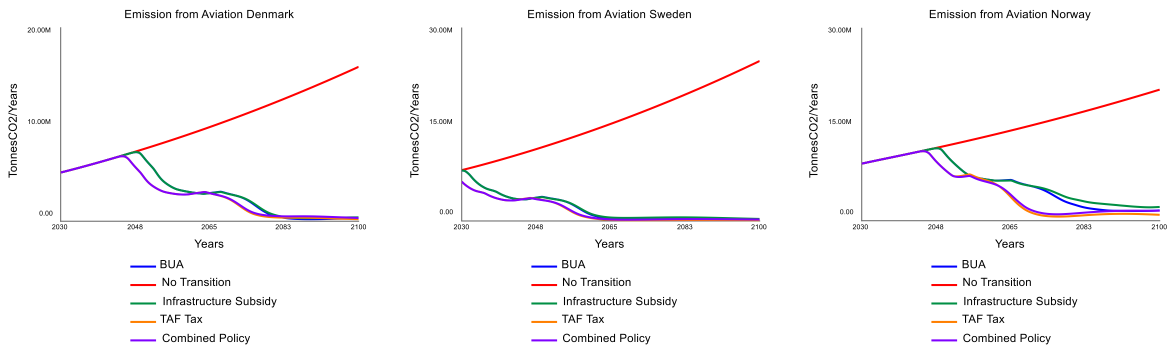

Figure 3.6 – Emission results for all Countries with All Policy Scenarios between 2030 and 2100

As *Figure 3.6* shows the policy did not have a large effect on emission reduction except for Norway, that manages to reach its lowest value in 2065 instead of 2085. The TAF tax means that the 'acceptable' price range of the other fuels is higher as it is more expensive to keep using TAF, which is not a shocking behaviour. The infrastructure subsidy had almost no effect as it followed the BUA scenario, except for Norway, where the infrastructure subsidy lowered the emission reductions. As the infrastructure subsidy removes the strength of the R1 – locked in loop the transition is not as black and white but more gradual, this means that it is a slower transition and thus, the other fuel that are not true zero remain for longer.

This phenomenon becomes clearer when combining the two policies, as hydrogen becomes available earlier (due to TAF tax) but as the R1 loop is weaker the transition is more gradual, thus the other fuels retain some of their original attractiveness meaning hydrogen does not dominate the fuel share once it becomes adopted (see *Figure 3.7* and *Figure 3.8)*.

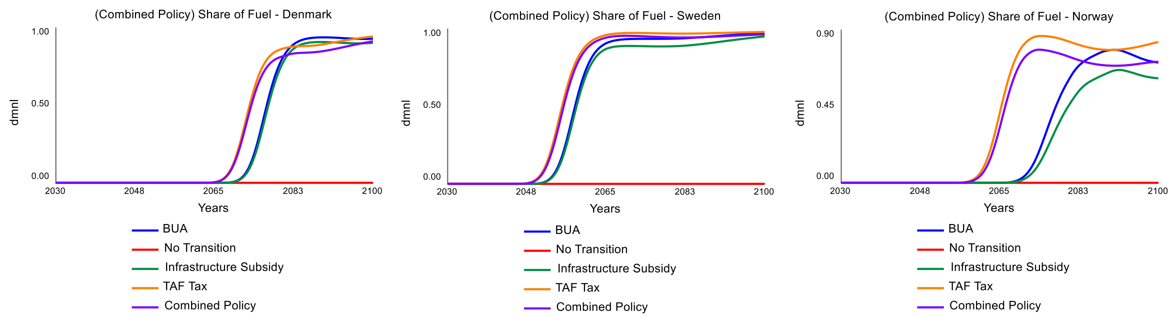

Figure 3.7 – Share of Fuel being Liquid Hydrogen in the Policy Scenarios

The high initial investment of hydrogen storage allows it to dominate the system since once it is transitioned, it costs too much to then transition back to drop-in fuels. The high cost is both a barrier to entry and a one-way street as the gate is locked behind, according to the model.

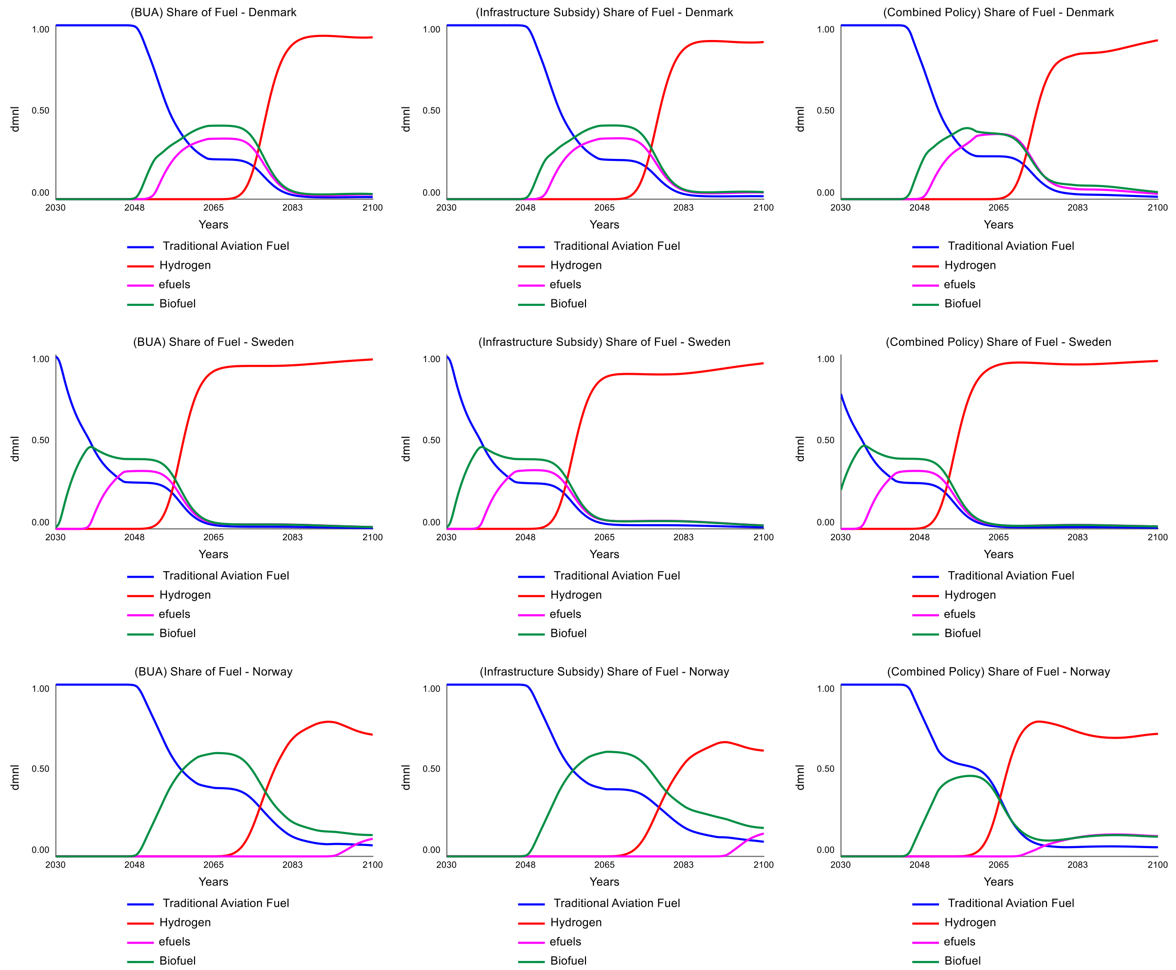

Figure 3.8 – Overview of Fuel share in Countries by all Policy Scenarios

3.5.3 Supply Focused Scenario

The third series of scenarios focuses on testing the effectiveness of supply side policies or interventions. The supply side policies that were tested can be found in *Table 3.2* including their aims. The stricter regulations based on emission targets follows the logic that a large emission gap causes the state to intervene by implementing subsides or encouraging investments into the alternative fuels to discouraging the usage of TAF.

Policy	*Aim*
Stricter Regulation of TAF based on Emission Targets	Aims to simulate the implementation of stricter policies on TAF to discourage the aviation industry from using it when the emission gap is larger.
Stricter Regulation of SAF based on Emission Targets	Aims to simulate the implementation of stricter policies on SAF to make it more attractive when the emission gap is larger.
OPEX Subsidy for Renewable Energy Production	Simulates subsidies targeting the OPEX of renewable energy production.
CAPEX Subsidy for Renewable Energy Production	Simulates subsidies on purchasing of new renewable energy production assets (wind turbines).

Table 3.2 – Overview of Supply Side Policies

Figure 3.9 shows the emission reductions per country under each scenario. As we can see, the policies do not seem to be a silver bullet solution to emission reduction. Evidently, the effectiveness of the policies lie in combining them. This reaffirms the findings of the policy scenarios where policies need to be combined and multifaceted to have an impact on complex problems such as sustainable transitions. The stricter policies based on the emissions intended to dissuade or encourage the selection of the fuels. The mechanism is that the larger the gap of emissions, the higher or lower (depending on if it is SAF or TAF), the fuel attractiveness becomes. This mechanism is not sensitive to changes in the input and the stricter regulations are therefore not effective in aiding the transition.

To be able to produce SAF there needs to be sufficient renewable energy available to reduce the lifetime assessment of CO2. Therefore, it can be stated that the renewable energy grid is crucial to any sustainable transition. The levelized cost of energy (LCOE), is the cost of the energy produced from renewable projects in terms of their lifetime production. LCOE has a great effect on the price of fuels, so giving out subsidies for either capital cost or operational costs was bound to be an effective solution as it reduces cost of fuel production and consequently is cheaper. Yet, the only noticeable effect is the starting time of the transition is moved to a few years earlier as shown in *Figure 3.9* and *Figure 3.10*. It is important to note that the differences in emissions stem from the use of different fuels in the transition and not from an earlier transition. Contrasting *Figure 3.9* and *3.10* clearly shows the similarities in all but the combined policy. The order of 'transitions' remains the same but in only the combined policy scenario does the transition start 5 years earlier and, in those cases, only Sweden and Norway are affected. This stems from high RES energy production present in those countries. Historically, Denmark has always been behind the other Scandinavian countries in renewable energy due to the lack of hydropower, and this is also reflected in the simulations.

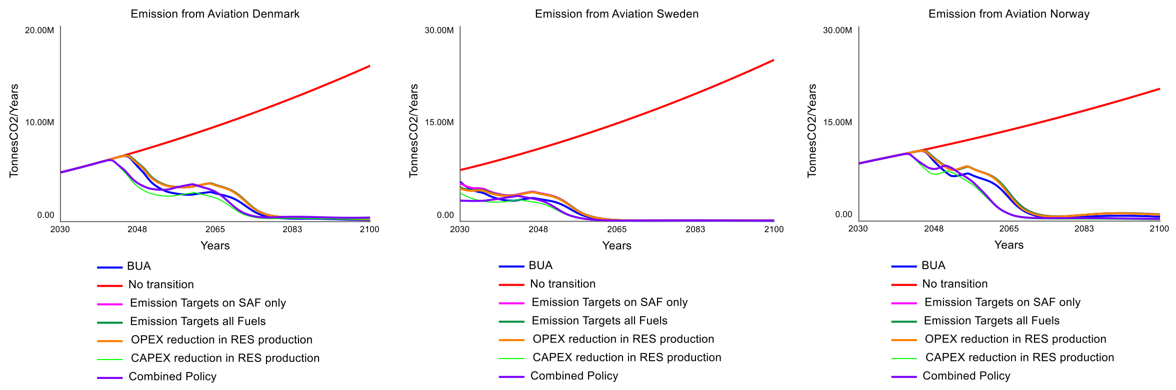

Figure 3.9 – Emissions from Aviation in Supply Side Scenarios

E-fuels is not used as much as in the BUA scenario since by the time it has become attractive enough to warrant adoption, hydrogen has reached or is about to enter the acceptable price range and thus, airports overlook e-fuels in favour of hydrogen adoption. Interestingly, only applying subsides to the CAPEX cost of RES production decreases emissions faster than the combined policy. The reason for this is that the fuels attractiveness is 'closer' in the other scenarios. So, when combining all the policies the fuels become more attractive earlier. Therefore, the fuels compete more for the share and consequently hydrogen become slower to transition so the other fuels are prevalent for longer. In contrast, reducing only the CAPEX costs of the RES production, means the fuels becomes available earlier but are less competitive overall (emission targets), and thus, will not counteract each other as strongly. This denotes a further complexity. It is not enough to invest in all fuels, as it can cause a slower transition due to the competition between them. There are always winners and losers in transitions, and it may be that it could be beneficial to have those pre-selected.

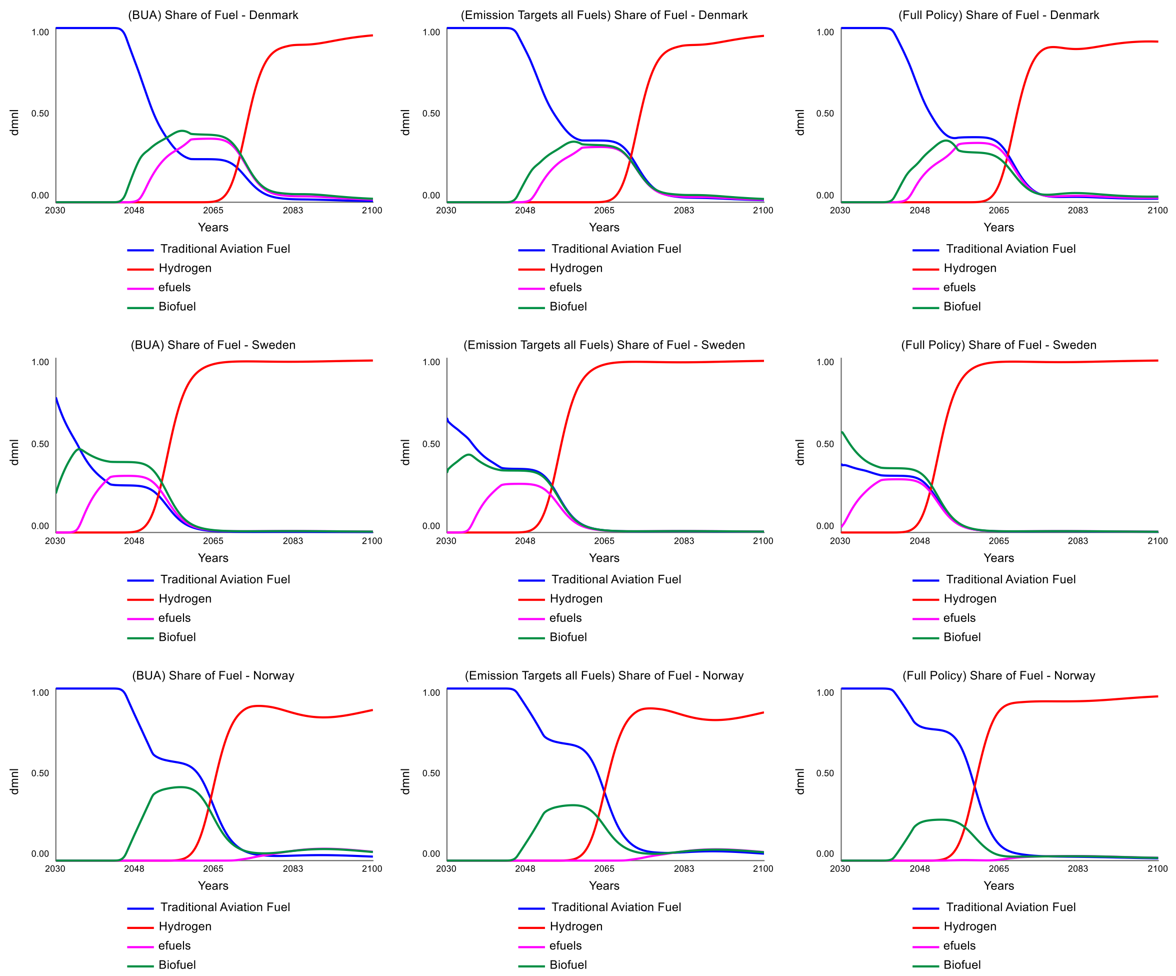

Figure 3.10 – Overview of Fuel Transitions with Emission Policies and Combined Policy

The revelations of these scenarios further highlight the need for a multifaceted policy targeting both the supply and demand side of SAF and that, as much as price is the main driver of demand, it is difficult to subsidise components of price to spur demand. In other words, handing out subsidies to renewable energy is alone not enough to reduce price far enough to cause an earlier transition. The fuel availability also needs to be factored in so subsidies to encourage production expansion would be effective but costly to the state. There is a trade-off between cost and effectiveness, hence, policymakers need to find the best balance between all the potential policies.

3.6 Summary

The output from the model follows previous literature in that biofuel demand should be the first one to increase, followed by e-fuels, and lastly hydrogen based energy carriers. This stems from multiple aspects such as the price of the fuel, its availability, the availability of the feedstock, CO2e emissions, cost of infrastructure, and energy content. There needs to be supply side support from the government or corporations for the transition to occur in an effective and timely manner, as without it there is less incentive to increase production capacity in order for price to decrease and make the fuels more attractive to the consumers, in this case the aviation industry. This indicates that policies that either target the price of traditional jet based fuels, to make it more expensive or policies that decrease the price of SAF can be effective tools for regulators.

Chapter 4: Discussion

This section is divided into two parts, the first part is the reiteration of the research questions and the answers found in this study. The second part is a further discussion of the results and unintended consequences and other possibilities that were not discussed in Chapter 3.

4.1 Research Questions: Revisited

The main research questions that this thesis sought to answer have been touched upon throughout the paper and were implicitly answered. This section will explicitly broach each question and the answer to it.

RQ: "What will be the transitional path of demand for sustainable aviation fuel?

This was discussed in depth in chapter 3 with the presentation of the simulation results and discussion on their validity. In short, biofuel will be the first to become available as it is the easiest to produce currently due to using easily accessible biomass feedstocks. Then e-fuels will increase, but due to inefficiency in the production process it will not overtake biofuel. Once hydrogen is cheap enough (assuming the hydrogen planes are constructed) it will dominate the market due to its high energy content, and no emissions.

The differences between the three countries come about due to the country's geography, renewable energy production, potential for PtX or PtL plans, and partnerships. According to the simulation results, Sweden is the first to start using SAF in 2030 while Denmark and Norway do not begin until the late 2040s. These transitions rely on technological advancement as well as investment from stakeholders as the fuels are either not able to be used due to technological limitations or are too costly to transition to. An alternative to full transitioning into either biofuel, e-fuel, or hydrogen is to blend the fuel (Ydersbond et al. 2020). As biofuel and e-fuel are drop-in fuels they can mixed together with TAF to reduce the emissions but not fully transition. The model does not consider this policy as the structure does not allow for blending requirements. In conclusion, the emission targets are not reached by 2050 but are in most cases low enough to be considered a non-loss.

SQ1: "What are the properties of the different SAFs and how does that affect the transition?"

The first sub question was discussed in chapter 1 where properties, production, benefits, and the drawbacks of each of the fuels were discussed. The key difference between the fuels is that biofuel and e-fuel are drop-in meaning there is relatively little infrastructure, fleet, or structural changes that are required, making it a cheaper transition. Hydrogen on the other hand, cannot use the same storage tanks, nor jet engines and therefore the cost of constructing and purchasing the required workers, materials, and the infrastructure itself needs to be factored into the cost of transition. This makes hydrogen not as attractive to transition to as the costs are extravagantly higher than for drop-in fuels. This raises the question of why hydrogen is even considered in the first place?

The reason hydrogen is considered a fuel of the future is twofold, it has triple the energy content (120 MJ/kg) and does not emit any CO2 if produced entirely from renewable sources. So, the benefits of using hydrogen as an energy carrier are greater than the drop-in fuels but the obstacles to it are also greater. That does not mean that the drop-in fuels will eventually be irrelevant as while these fuels may have lower emissions and the potential for negative emission rates, their production currently requires significant technological advancements and supply chain infrastructure that may not be feasible in the near future.

Ultimately, the choice of which low-emitting fuel to use will depend on a variety of factors such as the specific use case, technological feasibility, and economic considerations. It is important to continue exploring and investing in a range of low-emitting fuel options to ensure a sustainable and low-carbon energy future.

SQ2: "What are the main drivers of demand for sustainable aviation fuels in the Scandinavian aviation industry?"

The drivers of demand that need to be considered prior to transitioning to a different fuel are infrastructure, price per fuel, environmental benefits, and supply. These factors are dynamic and need to fall within a certain range that is deemed acceptable by the stakeholders. Out of those 4 drivers the price of the fuel is the paramount deciding factor as that cost will be repeatedly paid out to fill the storage rather than 'just' the cost of infrastructure. That is not to say that the cost of infrastructure is not important, it very much is, but if the price per kg of fuel is 10x as big as the price of oil based fuels then there will be no transition. Yet, if the cost of transitioning is 10x the cost of purchasing the traditional storage tanks, but the price per kg is low then there may still be a possibility of transitioning.

Therefore, the price is the deciding factor, and the other elements decide the range of acceptability around the price. If TAF is 1 USD/kg, the benefit of biofuel will decide how much more expensive the price of biofuel can be before the fuel is deemed beneficial enough to start to use. This calculation is done in comparison with the other fuels and thus, decides the desired share of fuel to use. Hydrogen is expensive but the environmental benefits are high, and it is costly to construct the necessary new storage, in comparison to e-fuel that can use the existing infrastructure and has less environmental benefits but is cheaper to produce. So, these factors are different per fuel and change as the other aspects of the world transition to sustainable and green options.

SQ3: "What strategies can be implemented to increase the demand for sustainable aviation fuels in the Scandinavian industry?"

There were two policies tested within the simulation but spread of policies is not limited by the three tested (infrastructure subsidies, TAF tax, and supply focused policies). The two tested highlighted that as price of fuel is the deciding factor, policies should aim to either increase the price of TAF through taxes or subsidise the price of SAF to make it more affordable and attractive. Targeting infrastructure through subsidies can provide benefits but is not as significant of an effect as price based policies. This would indicate that policies such as carbon pricing, carbon taxes, subsidies to supply to reduce the price for the consumers, or taxing high emission fuels are quite effective in aiding the transition.

Other policies include blending requirements that require the fuel share to either have a certain percentage be SAF or the fuel which is SAF is blended into the TAF which reduces the emissions slightly. This has been considered by the European Parliament (2021) for some time and some countries have already implemented such policies. Scandinavia is yet to do so but it is becoming more likely as the focus on sustainability is at the forefront of policy planning (Ydersbond et al. 2020).

It is important to note that policies are complex and multifaceted, and it may not always be possible to capture all the nuances and variables of a policy in a model. Therefore, it is important to recognize the limitations of models and use them as a tool to inform policy decisions rather than relying on them as the sole source of information.

4.2 Fuel for Thought

Herein, factors not included in the model and other considerations will be discussed. It is important to place the SAF within the larger body of literature, or at least within some of the important concepts within sustainability literature. In this case it will be a discussion on the possible rebound effects and its relevance to degrowth.

4.2.1 Electricity

Electricity is a potential crucial player in the sustainability transition within aviation as, if the electricity produced is from renewable sources there are no emissions. Its exclusions from the model stems from the inability of the modeller to endogenize the structure without using forced equations such as "start transition here" etc. Despite its barring, it is important to discuss the electricity as an energy carrier and the effect it could have in the future. For electrical planes to be functional several advancements need to be ready. Firstly, there needs to be effective battery storage that contains enough energy for either short, medium, or long haul planes (Dorn-Gomba et al. 2020). The planes need be redesigned to fit the new technology, depending on the pathways for the technology such as propulsion, batteries, airframe, electrical machine technology (Adu-Gyamfi & Good 2022). There is wide speculation and forecasting on when this technology will be ready for commercial use; DNV predicts it will be ready in small amounts by 2040 and Avinor assumes the technology will be ready within a 10-15 year timeframe for short haul flights (DNV 2022b; Reimers 2018). There seems to be hope and optimism that electrical planes (at least for short haul flights) will be introduced in the 2040s but not be scaled up until later.

The delay in up scaling stems from the aforementioned technology but also the renewable energy production since if the electricity does not come from decarbonized production, then the emission aspect is for naught. The challenges are similar to the transition to hydrogen as technology, infrastructure, and the fleet need to be switched for the energy carrier to be used. Thus, if the model had included electricity it would compete against hydrogen and be introduced around the same time and divide the fuel share 50/50 if the technology is ready on time. The challenge if the technology is not ready on time is due to the lock in mechanism, meaning if hydrogen dominates, the cost of transitioning to electricity would be too large and the benefits marginal. Thus, unless the benefits are larger, and the transition cheaper (remember all the drivers), timing is crucial to be able to compete.

There are electrical flights in use but only a handful and currently they are barely able to fly the 500km minimum for a short haul flight, for it to be usable by the 3500km+ planes there is still advancement needed (Lev et al. 2019). It is important to note that there is a scale of electrical flights from fuel and electric, to full electric. These hybrids allow for less emissions and longer flights simultaneously as the electric engine part of the power would then come from emission free electricity.

4.2.2 Rebound and Ripple Effects

A rebound effect, or Jevons paradox, is traditionally defined as an increase in efficiency leading to greater use (York and McGee 2016). However, over time the definition has evolved from the traditional energy-economic setting to a more general definition of the difference between potential environmental benefits and the actual environmental benefits. In other words, a sustainable action resulting in unsustainable consequences (Santarius and Soland 2018; Laurenti et al. 2015). In the aviation industry, an increase in fuel efficiency could result in more people flying as less fuel means less costs and thus cheaper tickets which subsequently increases demand thus, unless the SAF supply chain, fleet construction, and transport sectors are fully decarbonized emissions would increase resulting in a discrepancy between the sustainable action and the potential environmental benefit (Miyoshi & Fukui 2018).

So even though SAF will reduce the carbon footprint of the aviation industry, there is the potential of worsening any contribution to mitigate climate change due to the aforementioned reason. It is therefore important to guide the industry and plan accordingly as to not negate any of the positive effects. Such policies could be to promote alternative modes of transport, vacationing more locally, and increasing prices to discourage frequent flyers. The possibility of rebound effects highlights the unintended obstacles and challenges that occur during sustainable transitions on global/national scales. The transition of one industry inevitably needs the decarbonization of another while balancing the growth in industry. If an industry is growing exponentially while transitioning it is akin to moving the goal post constantly, unless, in the case of SAF the production is growing more rapidly than demand. So, is the answer degrowth? This potential degrowth of the industry is a double edged sword as decreasing demand will lead to less revenues and thus, the cost of transition may be too much while at the same time the less passengers, the less flights needed and thus, less CO2e emitted.

There is a lot of uncertainty regarding policy effectiveness, design, and conceptualization, thus regardless of which scenario becomes reality the important thing is focusing on a holistic policy that can foresee or at least attempt to mitigate any unforeseen consequences in the long term. Overall, while SAF has the potential to play a role in decarbonizing the aviation sector, it must be implemented within a comprehensive and sustainable framework to avoid unintended consequences and ensure long-term sustainability.

This framework has to, in addition to ensuring long-term sustainability, also deal with rebounds and ripples in other industries. The aviation sector does not operate independently from other industrial and transport sectors, and thus, a sustainable action, such as switching to biofuel has the possibility of causing externalities in other fields. In the case of biofuels, it would the agricultural sector as it would increase demand for water and arable land. Furthermore, all fuels need the supply line to be green as well so that the lifetime-assessment CO2 is reduced and not only the fuel emissions. This complexity of upstream and downstream ripples that SAF has the potential of causing, or any industry for that matter, is an unavoidable obstacle requiring cooperation to navigate.

Chapter 5: Conclusion & Limitations

The predictions presented using the SD model show that the national emission targets will be difficult to reach unless there is a ramping up of investments into production and technology. To be able to increase SAF demand it needs to be economically viable for the airports to start purchasing the fuel as well as invest in necessary infrastructure. That means that the price of the fuel needs to decrease. The industry is currently facing a chicken and egg misalignment where there is not enough supply to spur demand but the demand is low so there is little incentive to increase production capacity. The results of this study indicate that policies such as varying price schemes to either increase the price of traditional fuel or decrease the price of SAF would be particularly effective.

Under the current policies and technological level (BAU scenario), the transition would first start a switch to biofuel, followed by e-fuels after which hydrogen would dominate, assuming the technology to use hydrogen as an energy carrier would be available. The specific order is due to the high efficiency of biofuel while there is low efficiency in the production of e-fuel as well as production capacity. Additionally, the challenges with each fuel and the fuels properties cause varying levels of attractiveness and despite the easier transition to biofuel there are still emissions which can lead to externalities in the agricultural sector.

These challenges ranging from the geographical, economic, environmental, and social aspects deter and disallow a rapid transition. Regardless of which fuel will be used in the future, it is important to establish a strong collaboration between private and public organisations to ensure a rapid decarbonization of the aviation industry.

There are several limitations that can affect the validity and generalizability of this research project. The exclusion of electricity in the simulation model creates uncertainties as it does not show the whole picture. Additionally, the supply side of the model is not endogenously driven and therefore, does not consider feedback mechanisms. This means the results could vary if the feedback was accounted for. It is important to note that all exogenous drivers were tested to see whether the data input is incorrect or unrealistic but that is different than the potential endogenous behaviour could be. In general, due to the scale of the supply side structure, it was simplified and thus, invites uncertainty regarding the development of the production capacity. For the future work it would be beneficial to combine a demand side and supply side model to see the ‘full’ interaction between the two.

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Appendix A: Simulation Report

In this section the values of the parameters in different scenarios will be presented so they can be reproduced (Rahmandad & Sterman 2012). The ‘business as usual’ (BUA) will be the scenario presented in Appendix C: Model Documentation or can calibrated to using the original values.

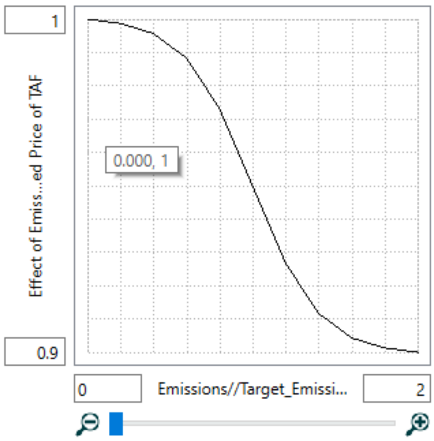
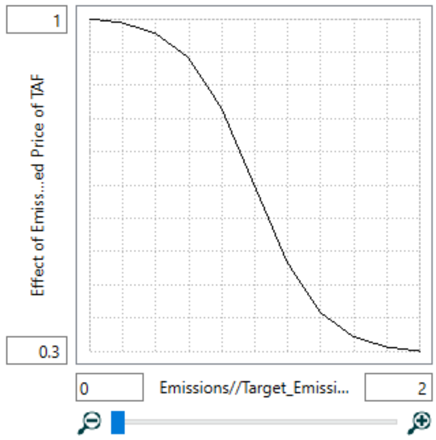
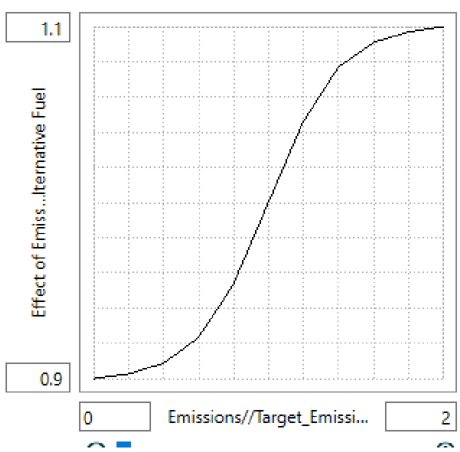
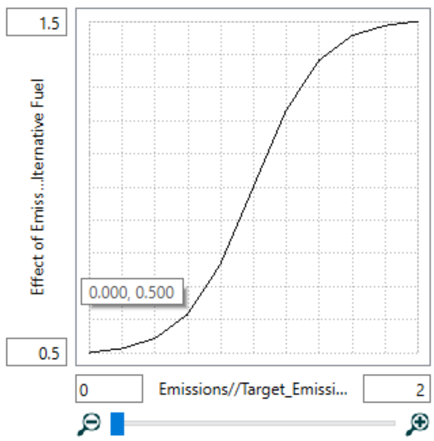
No PtX plan or Emission Targets

Variable	Original Value	New Value
Boost from PtX Plan		
Sweden	H2 = 1.1, Efuels = 1.15, Biofuel = 1.1	All set to 1
Norway	H2 = 1.3, Efuels = 1.15, Biofuel = 1.1	All set to 1
Denmark	H2 = 1.4, Efuels = 1.15, Biofuel = 1.1	All set to 1
Emission Target		
Sweden	IF TIME>2008 AND TIME<2030 THEN HISTORY(Emissions*0.63, 1990) ELSE IF TIME>2030 THEN 0 ELSE Emissions	= *Emissions*
Norway	IF TIME>2008 AND TIME<2030 THEN HISTORY(Emissions*0.70, 1990) ELSE IF TIME>2030 THEN 0 ELSE Emissions	= *Emissions*
Denmark	IF TIME>2008 AND TIME<2030 THEN HISTORY(Emissions*0.63, 1990) ELSE IF TIME>2030 THEN 0 ELSE Emissions	= *Emissions*

Policy Scenarios

Variable	Original Value	New Value
Tax on TAF		
Fuel price	Data	Data*STEP(1.5, 2024)
Infrastructure Subsides		
Initial Investment cost[Hydrogen]	228.57	228.57*0.5

Supply Side Scenarios

Variable	Original Value	New Value
Effect of Emission on perceived price of TAF		
Effect of Emission on perceived price of Alternative Fuel		
OPEX	35000*22	20000*22
CAPEX	3e6	(3e6*0)+1.8e6

Appendix B: Sensitivity Analysis

The most interesting results from the sensitivity analysis are presented here. The analysis was performed on three types of parameters: 1) adjustment times, 2) graphical functions, and 3) assumptions. The test was done on all parameters but as there are over 900 variables in the model (with arrayed dimensions) only interesting and sensitive results will be presented below. The sensitivity tests were performed with Stella 3.2's sensitivity tool with Sobol sequencing sampling and uniform distribution. The graphical functions were manually distorted to see if there was a change in behaviour. As the model is arrayed by type of flight, country, and fuel only certain dimensions will be shown. All three countries will always be displayed but the fuel will only be showing the fuel it directly affects or traditional aviation fuel as if there is no decline in the actual share of fuel for TAF then there is no transition. One can, therefore, defer the rest of the fuel behaviour from TAF.

Adjustment Times

In general, the adjustment times only affect the timing of the transition which was the expected behaviour. Increasing the delays meant a slower transition and decreasing the delays indicated a faster transition. There was nothing unexpected situation or anomalies in the simulations.

Setting Fuel Strategy Time (Uniform distribution, variation: 0.5 to 15 years)

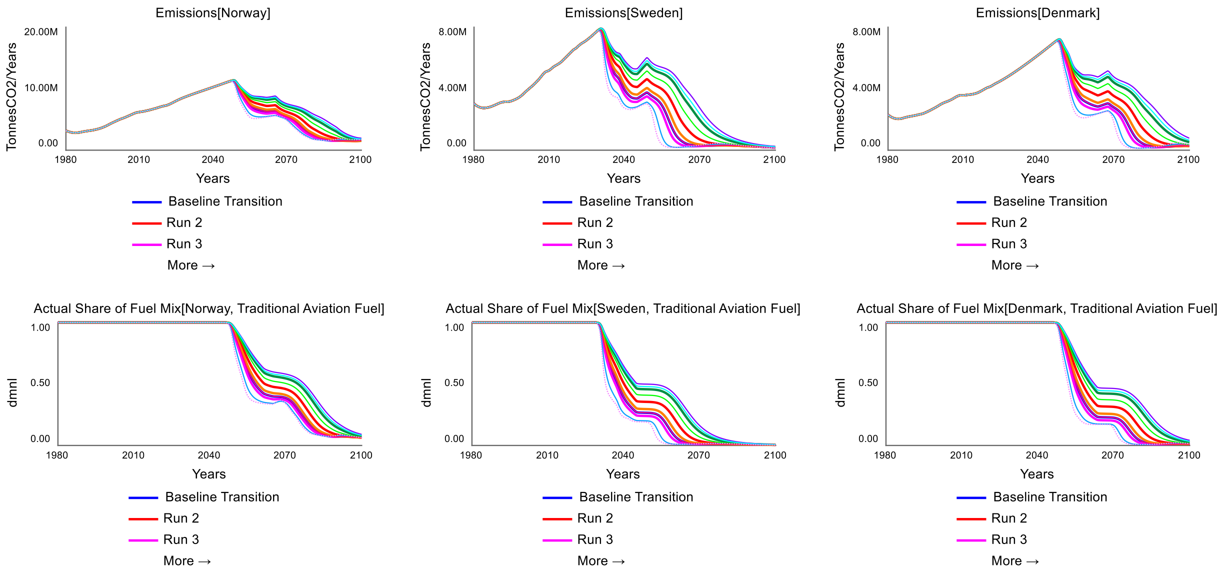


Figure B.1 – Sensitivity for Setting Fuel Strategy Time

The model is relatively sensitive to changes in 'setting fuel strategy time' which is the expected behaviour. This adjustment time is the delay in adjusting the desired share of fuel mix from the fuel attractiveness, so if it is a faster reaction then the airport will want to construct the infrastructure faster than in a larger delay time. If the infrastructure is available sooner, then emissions will be reduced earlier and cause an earlier transition. There is no data on this adjustment time, but the sensitivity shows that fast movers can cause an earlier transition.

Asset Lifetime (Uniform distribution, variation: 5 to 50 years)

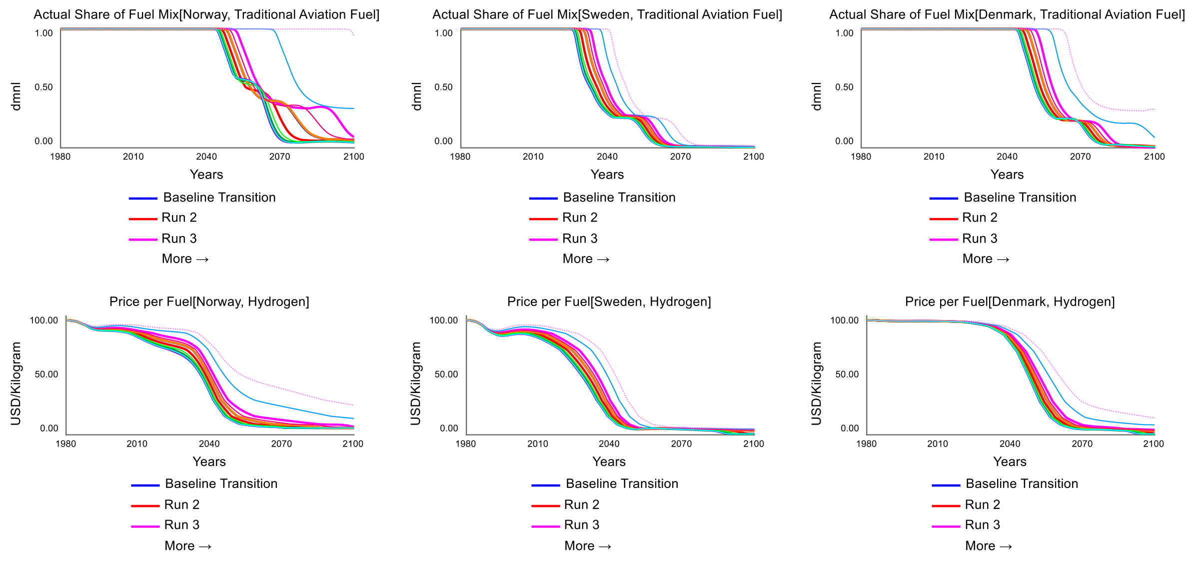


Figure B.2 – Sensitivity for Asset Lifetime Infrastructure

The asset lifetime for infrastructure was decided upon after being calibrated and tested for sensitivity. A lower lifetime results in stock of infrastructure depleting faster thus making it more difficult to gather the necessary infrastructure to meet demands, so the lowest variation of 5 years is less than the time it takes to order and construct to the desired level of infrastructure it becomes easier to switch but harder to keep up with demand. In the higher variation, as there is no infrastructure as 'deconstruction' flow the infrastructure remains and stays part of the fuel mix for much longer which complicates the transition as it would not make financial sense to switch to another infrastructure if there is other available especially as biofuel and e-fuel can use the same infrastructure.

Ordering New Planes (Uniform distribution, variation: 1 to 35 years)

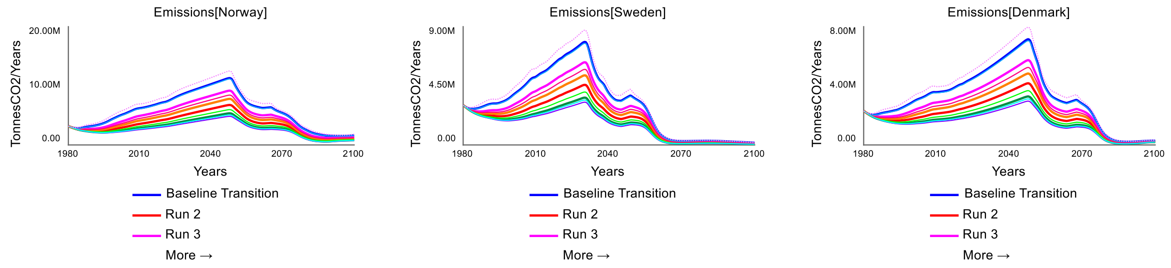


Figure B.2 – Sensitivity for Ordering New Planes

The fleet adjustment time is only sensitive to three aspects of the model: the fleet, fuel storage and emissions. Taking more or less time to order new planes for the fleet means that there will be either more or less planes resulting in a lower or higher fuel demand. The higher or lower demand results in more or less emissions. It does not affect the transition as the demand for aviation is not factored into the decision-making process of the airports for fuels (only accounting for size of fuel storage).

Capacity Adjustment Time (Uniform distribution, variation: 1 to 35 years)

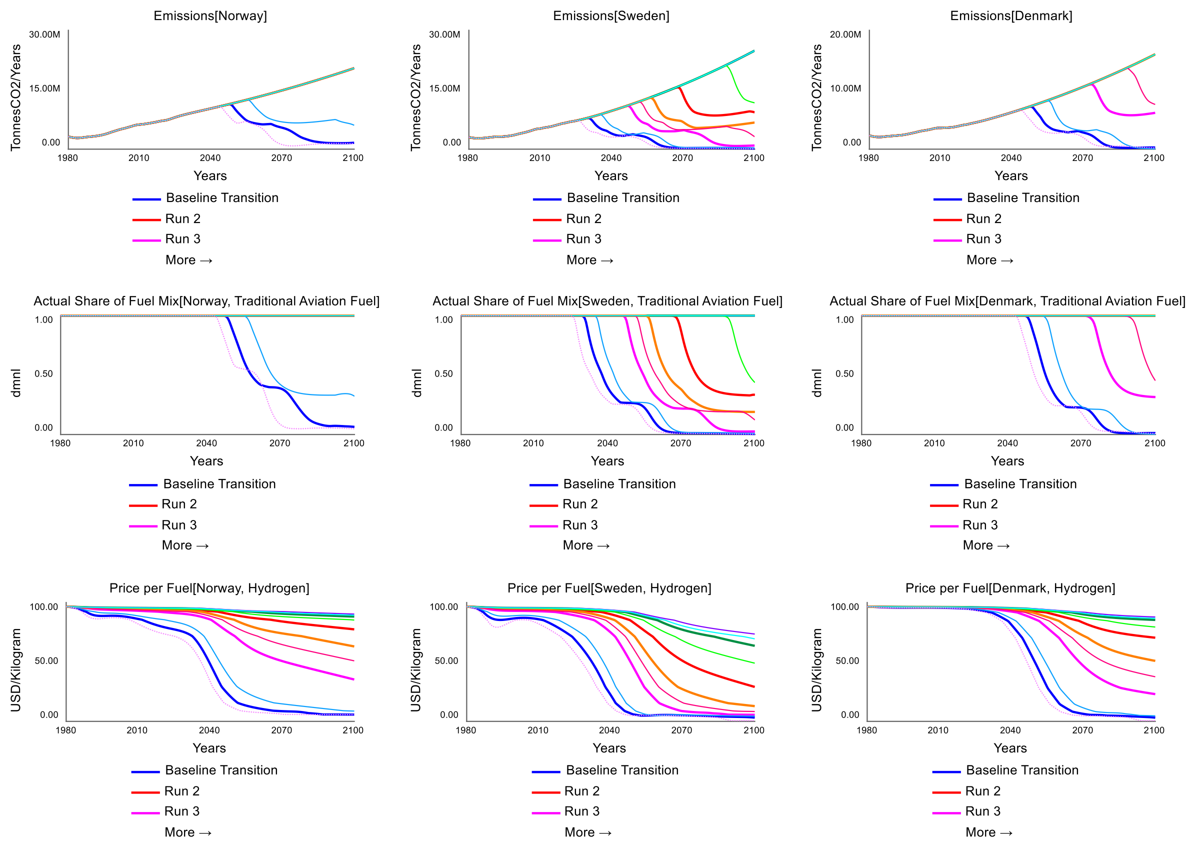


Figure B.3 – Sensitivity for Capacity Adjustment Time

The capacity adjustment time is part of the material delay for constructing fuel production capacity. So, logically it would be quite the sensitive variable. If there is not enough fuel capacity the price will not decrease, the availability will not be as strong and consequently, emissions will not decrease as rapidly. The supply aspect of the sustainable aviation fuel transition is detrimental to its success and thus, any large delays can ruin the potential of any fuel.

Assumptions

The assumptions that are made within the model has a large effect on the model if they are on the supply and decision side and less so if they are part of the aviation demand sector. It highlights the importance of supply side policies and that there needs to be sufficient supply prior to transitioning.

Price of Traditional Aviation Fuel (Exogenous Data, RAMP function)

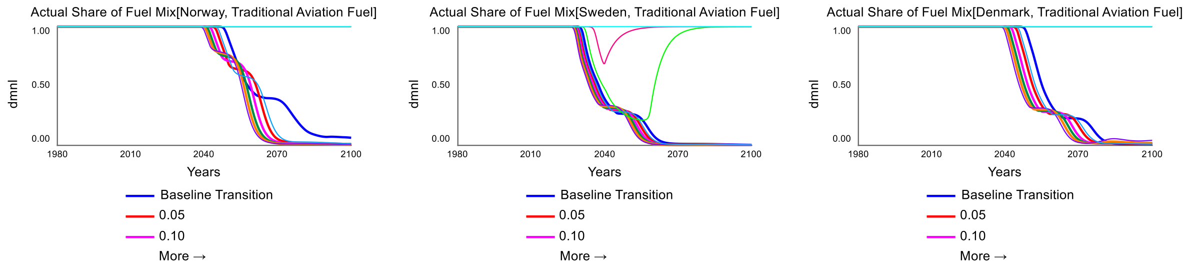


Figure B.4 – Sensitivity for Price of Traditional Aviation Fuel

The price of traditional aviation fuel (TAF) is sensitive to any and all changes. Price is main driver of the model, so it was evidently going to be sensitive. A RAMP function starting in 2022 with the change from -0.20 to 0.35 was used to test the data and variable. A negative value meant a decline in price of that value annually, and a positive meant an increase. As the price is relatively low prior to the ramp function, declining it even further rapidly sends it to 0 meaning there is no cost to the fuel and thus, there is not an inch of consideration to transition. No company would transition from a free option. Similarly, increasing the price increases the speed of the transitions as the other options are much cheaper. The interesting aspect to this is that the price of transition is important and, at least according to traditional economic thought, the transition would be a faster process if the price is reduced. This hints at possible policies, such as tariffs, carbon pricing, and subsidies that the government can implement. Yet, implementing those policies before the supply side is ready could have unintended results. such as declining demand and beneficial emission reductions.

Elasticity of GDP pc to Flights per Person (Uniform distribution, variation 0.5-2.5)

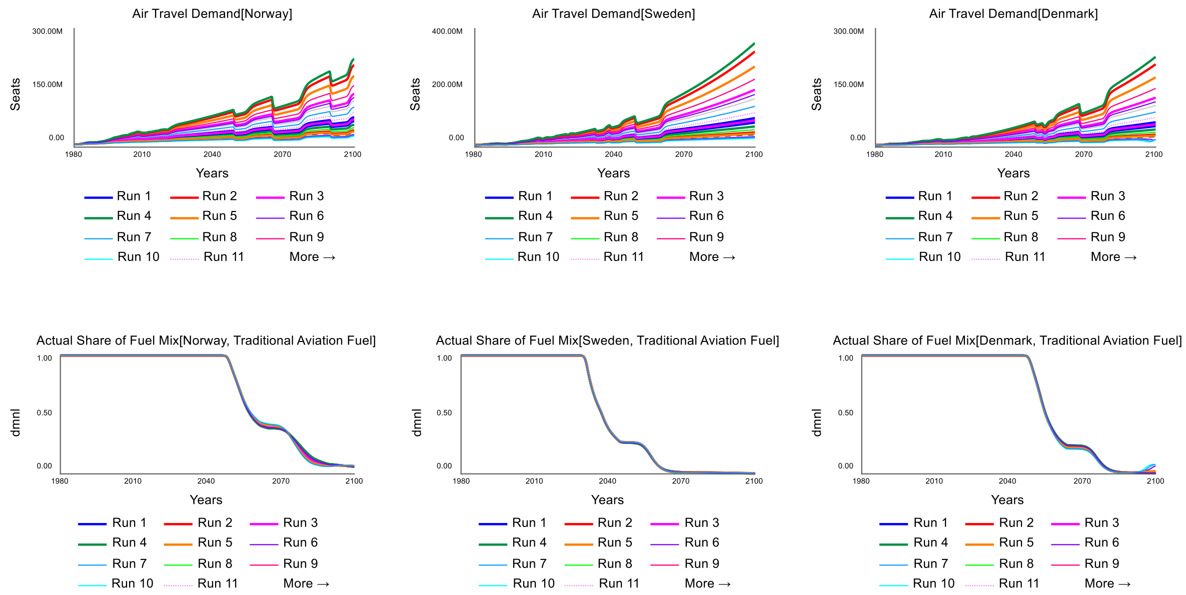


Figure B.5 – Sensitivity for Elasticity of GDP pc to Flights per Person

The elasticity of GDP pc to Flights per Person is going to be sensitive as it reflects the effect of a change in variable X to variable Y. The upper three graphs show the simulation space the uniform distribution has on air travel demand and an alteration in elastic will greatly change demand. However, the interesting aspect is that this has no effect on the transition. Realistically, the less travel demand, the less money to spend so transitions would occur slower, but as that link is not present in the model, transition continues without delay. Now, it could be argued that the transition will still occur despite the loss in revenue as the overall fuel demand will be easier to meet as there is less demand for it and thus, the money spent is relatively the same share as if there was more demand.

Normal Share of Energy Consumption[Hydrogen](Uniform Distribution, variation 0.02-0.2)

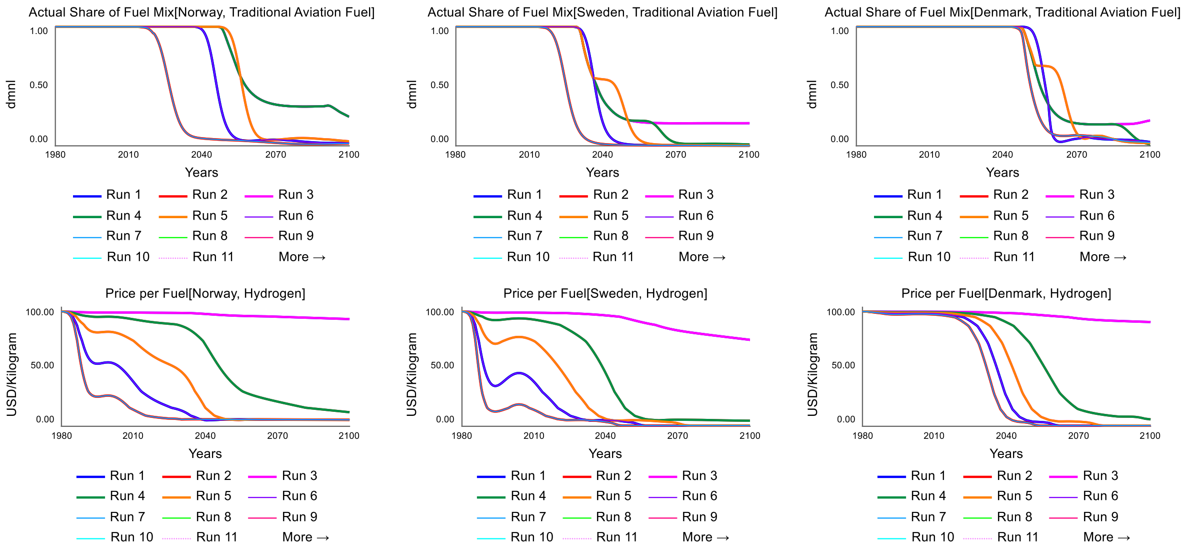


Figure B.6 – Sensitivity for Normal Share of Fuel Energy Consumption[Hydrogen]

The normal share of fuel energy consumption is the initial share of RES that is being directed to fuel production. It is arrayed by fuels so TAF, hydrogen, e-fuels, and biofuel all have their own values. In this case, only hydrogen will be presented as the expected result is equal between the fuels when simulating different initial shares. The higher the initial share the more fuel production exists and thus, the subsequent low price and high fuel availability will make it an attractive fuel to transition to. A large supply and little demand mean that prices will be low so this sensitivity is both expected and can show that supply focused policies could work at least until one considers the supply need for profit as well.

Share of Demand per Type of Flight (Uniform Distribution, variation 0.1 to 1)

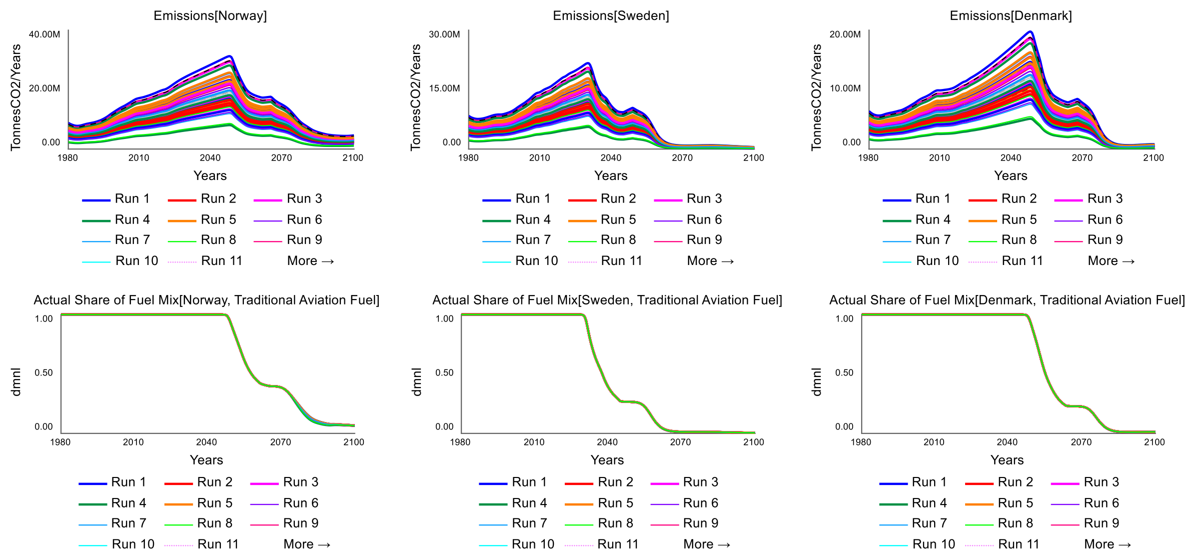


Figure B.7 – Sensitivity for Share of Demand per Type of Flight

Long haul planes emit more and require more fuel due to the weight of more passenger and luggage, the longer journey, and heavier take off and landings. So, altering the share of demand per type of flight (all three types, 50 runs) meant that in cases where more of the demand was for long haul trips then the emission and energy demand would increase. Interestingly enough, the transition from TAF is not affected at all by the changes. As the supply side is not influenced by the demand for aviation but only the demand for SAF relative to TAF, the transition remains the same despite the larger possible emissions. As the transitions still occurs within the baseline timeframe, the emissions are still almost reduced to 0 in most of the scenarios which is an indication of hope that the sector despite its large emissions can still reach a carbon free world.

KWh needed to produce 1kg of Fuel[Hydrogen] (Uniform Distribution, variation 5 to 150)

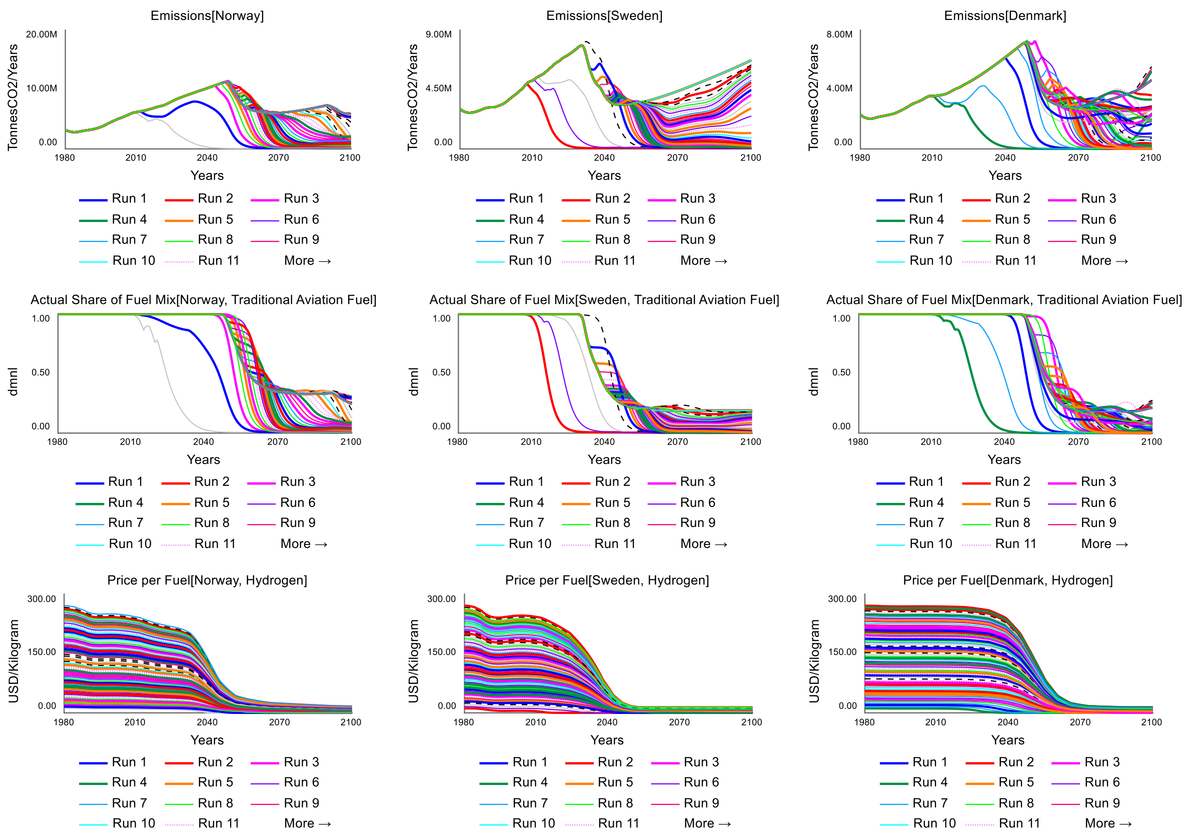


Figure B.8 – Sensitivity for KWh needed to produce 1kg of Fuel

The energy requirement in fuel production alters the amount of fuel that can be produced. So, reducing the energy intensity of the activity means that the supply of fuel can become larger much faster as there is less capacity needed to produce substantial amounts of fuel. Interestingly, changing the hydrogen requirement seems to also affect the other fuels as in some scenarios the emissions start to increase after switching to the other fuels. Those are related to when the energy requirement is high but as the benefits of hydrogen are also high it becomes a hard decision and thus, there is some switching between the fuels until hydrogen becomes the winning fuel through the locking in mechanism.

Graphical Functions

The graphical functions are used sparingly in the model but the parts where they are presented are the most important drivers of the model so it is important to see the effect that different functions could have on the model. There is no automatic distortion for these graphs so it will be done manually in 3 different scenarios to see how a reduced effect, altered shape, and reverse shape could have on the model. The findings show that the graphical functions present in the fuel attractiveness sector greatly affect the model as reversing or reducing the function alters the behaviour wildly.

Effect of Cost of Energy on Fuel Attractiveness (Original: S-shaped between from 0 to 2)

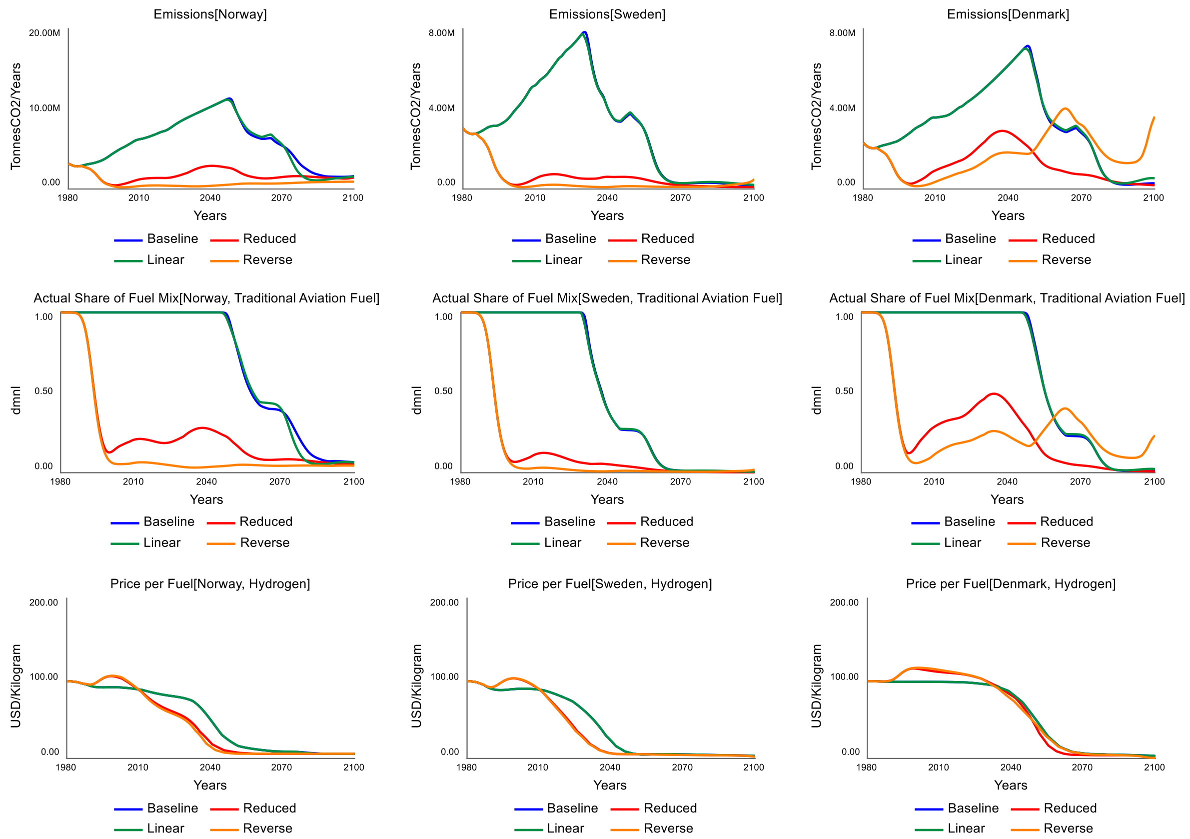


Figure B.9 – Sensitivity for Effect of Cost of Energy on Attractiveness

The graphical function of effect of cost of energy on attractiveness represents the relationship between low prices and fuel attractiveness, where the lower the price the more attractive the fuel. Thus, reducing the output of the graphical function meant that the price effect will be smaller when compared to TAF hence the earlier transition. Interestingly, reduction of the effect and reversing the effect has the same effect. That is due to the other drivers still being strong. Reversing the graphical function means the fuel is attractive when it is expensive so that when the price is high, as it is before the production can ramp up, they start to transition.

Effect of Hydrogen Share on Demand through Price (Original: S-shaped from 1 to 0.75)

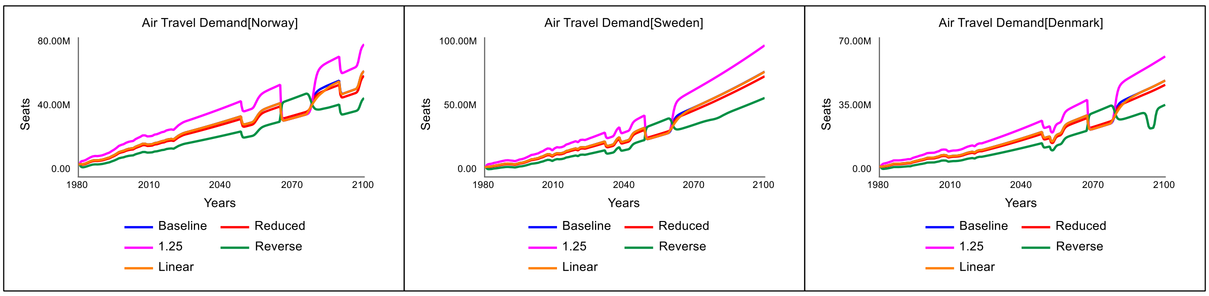


Figure B.10 – Sensitivity for Fuel Share on Demand through Price

The results are as expected since it is not a large effect (between 1 and 0.75) so trying different functions, and shapes had little to no effect. *Figure B.10* only shows the air travel demand as it was the aspect where it had the greatest effect. Reversing the shape only reversed the oscillations and altering the shape did not have large enough effect to be noteworthy.

Effect of Fuel Supply on Fuel Attractiveness (Original: Exponential from 0 to 1).

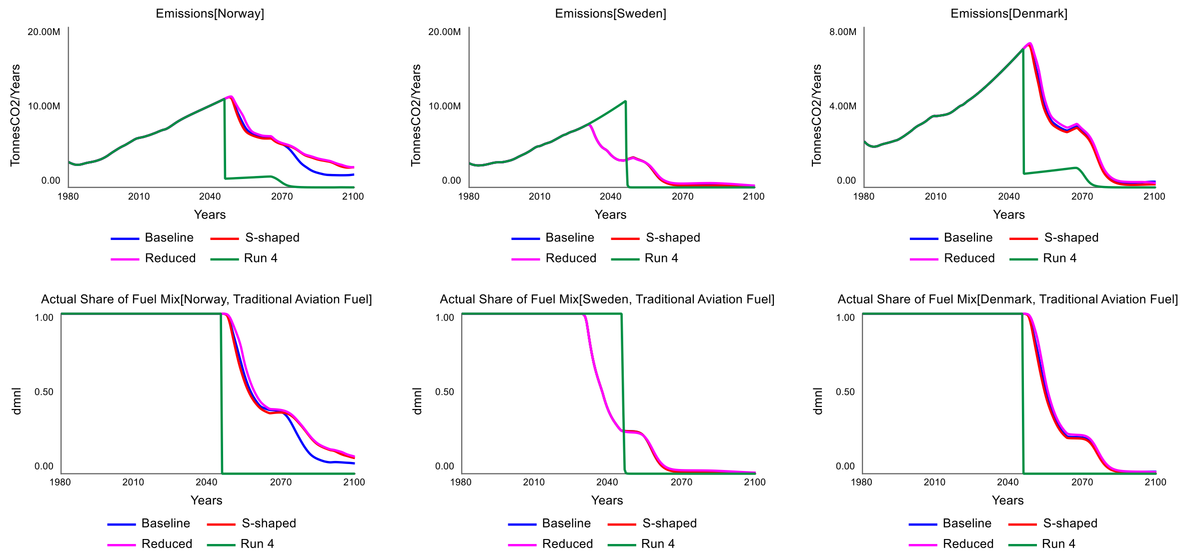


Figure B.11 – Sensitivity of Effect of Fuel Supply on Fuel Attractiveness

The only change that the model was sensitive to is the reversing of the effect (from 1 to 0) as it removes the supply from the decision at least until SAF production rivals the TAF production. The decrease in TAF in the fuel mix comes from the fact that hydrogen is still not able to out produce TAF and drop-in fuels, so the attractiveness of biofuel and e-fuel becomes 0 quickly, which leaves hydrogen but as it is still relatively expensive the transitions still take time until it reaches the infliction point. It demonstrates that supply is not the only factor when considering transitioning from high emission fuels.

Appendix C: Model Documentation

Non-sector Variables
Name: Accumulated_Pollution_in_Atmosphere_from_Aviation[Country](t) Equation: Accumulated_Pollution_in_Atmosphere_from_Aviation[Country](t - dt) + (Emissions[Country]) * dt INIT Accumulated_Pollution_in_Atmosphere_from_Aviation[Country] = 0 Unit: TonnesCO2 Documentation: This is the total emissions since 1980. It accumulates the annual emissions and stores it in the stock. There is no outflow as the intention is to use this stock as an KPI to show reduction compared to 1980 level.
Name: Actual_Share_of_Fuel_Mix[Norway, Traditional_Aviation_Fuel] Equation: "Re-Array_Variable"[Norway,Traditional_Aviation_Fuel]//SUM("Re-Array_Variable"[Norway,*]) Unit: dmnl Documentation: This is the actual share of fuels being used at the airports. It takes the storage available and divides it by the total storage as to find what percentage of the storage is made for each fuel.
Name: Actual_Share_of_Fuel_Mix[Norway, Hydrogen] Equation: "Re-Array_Variable"[Norway,Hydrogen]//SUM("Re-Array_Variable"[Norway,*])
Name: Actual_Share_of_Fuel_Mix[Norway, efuels] Equation: "Re-Array_Variable"[Norway,efuels]//SUM("Re-Array_Variable"[Norway,*])
Name: Actual_Share_of_Fuel_Mix[Norway, Biofuel] Equation: "Re-Array_Variable"[Norway,Biofuel]//SUM("Re-Array_Variable"[Norway,*])
Name: Actual_Share_of_Fuel_Mix[Sweden, Traditional_Aviation_Fuel] Equation: "Re-Array_Variable"[Sweden,Traditional_Aviation_Fuel]//SUM("Re-Array_Variable"[Sweden,*])
Name: Actual_Share_of_Fuel_Mix[Sweden, Hydrogen] Equation: "Re-Array_Variable"[Sweden,Hydrogen]//SUM("Re-Array_Variable"[Sweden,*])
Name: Actual_Share_of_Fuel_Mix[Sweden, efuels] Equation: "Re-Array_Variable"[Sweden,efuels]//SUM("Re-Array_Variable"[Sweden,*])
Name: Actual_Share_of_Fuel_Mix[Sweden, Biofuel] Equation: "Re-Array_Variable"[Sweden,Biofuel]//SUM("Re-Array_Variable"[Sweden,*])
Name: Actual_Share_of_Fuel_Mix[Denmark, Traditional_Aviation_Fuel] Equation: "Re-Array_Variable"[Denmark,Traditional_Aviation_Fuel]//SUM("Re-Array_Variable"[Denmark,*])
Name: Actual_Share_of_Fuel_Mix[Denmark, Hydrogen]

Equation: "Re-Array_Variable"[Denmark,Hydrogen]//SUM("Re-Array_Variable"[Denmark,*])
Name: Actual_Share_of_Fuel_Mix[Denmark, efuels] Equation: "Re-Array_Variable"[Denmark,efuels]//SUM("Re-Array_Variable"[Denmark,*])
Name: Actual_Share_of_Fuel_Mix[Denmark, Biofuel] Equation: "Re-Array_Variable"[Denmark,Biofuel]//SUM("Re-Array_Variable"[Denmark,*])
Name: Annual_Emissions Equation: 1 Unit: Year Documentation: The is the emissions time. It is set to 1 year as the emissions are measured annually.
Name: Average_Distance_in_Kilometers_flown_per_Type_of_Flight[Short_Haul] Equation: 500 Unit: Kilometers/Flights Documentation: This is the average distance in km flown per type of flight and it was calculated in two steps. First step was to take the median value in km per category of flight. Short haul is defined as any flight between 0-1500 km. Medium haul is any flight between 1500-3500 km and long haul is any flight above 3500 km. Second step was to reduce it a little to account for the fact that the dispersion of flights falls closer to the short haul. Most flights are the shorter flights hence the median being skewed towards the short end.
Name: Average_Distance_in_Kilometers_flown_per_Type_of_Flight[Medium_Haul] Equation: 1750
Name: Average_Distance_in_Kilometers_flown_per_Type_of_Flight[Long_Haul] Equation: 3500
Name: Average_Seats_per_Type_of_Flight[Short_Haul] Equation: 80 Unit:Seats/Flights Documentation: The average seats per type of flight is based on the most common models within each category. For the short haul flights, it is the CRJ-900 which has 80 seats. Medium haul is based on the Boeing 737 which is 140 seats. Lastly, the long-haul flights is taken from the Airbus 330 which has 330 seats but since the market is evenly split between that and a less seated flight the long haul flight is reduced to 280 seats. This was checked against reference fleets so that it matches it (SAS 2023; Widerøe 2023; Norwegian 2023).
Name: Average_Seats_per_Type_of_Flight[Medium_Haul] Equation: 140
Name: Average_Seats_per_Type_of_Flight[Long_Haul] Equation: 280
Name: Aviation_Demand_in_Distance[Country, Flights]

Equation: Possible_Flights_per_Year*Average_Distance_in_Kilometers_flown_per_Type_of_Flight[Flights] Units: Kilometres/Year Documentation: To find the total kilometres flown we multiply the trips that occur every year by the average distance flown by each type of flight together. Thus, finding the kilometres flown per year.
Name: Aviation_Demand_Seats_per_Type_of_Flight[Country, Flights] Equation: Air_Travel_Demand[Country]*Share_of_Seat_Demand_per_Type_of_Flight[Flights] Units: seats/Year Documentation: Multiplying the aviation demand by the share of the flights that belong to each of the three categories (Short haul, Medium haul, and Long haul) shows the allocation of flights per category. Short haul is defined as any flight between 0-1500 km. Medium haul is any flight between 1500-3500 km and long haul is any flight above 3500 km.
Name: Aviation_Demand_Trips[Country, Flights] Equation: Aviation_Demand_Seats_per_Type_of_Flight/Average_Seats_per_Type_of_Flight[Flights] Unit: Flights/Year Documentation: To be able to calculate the size of the fleet the seats need to be converted to flights (trips). This is done by dividing the total demand by the seats per plane which gives the number of flights that need to be done to be able to meet the demand. The reason to find the fleet instead of assuming that demand can be meet is related to the fact that certain fuels require specialized planes and thus, needs to be present in the model.
Name: Aviation_Energy_Demand_per_Type_of_Flight[Country, Flights] Equation: Aviation_Demand_in_Distance*Energy_Efficiency Unit: MJ/Year Documentation: The input into the aviation energy demand is the sum of total kilometres flown and the energy efficiency. This gives the energy used up per kilometre multiplied together with the total kilometres
Name: Change_in_Desired_Storage[Country, Fuel] Equation: (Indicated_Desired_Storage-Desired_Storage)/Time_to_update_Desired_Storage Unit: Kilograms/Years Documentation: This is a goal-gap formation that increases the desired storage towards the indicated desired storage. If the flow goes negative if the stock is larger than the indicated and goes positive if the opposite is true
Name: CO2_released_per_Unit_of_Usage[Traditional_Aviation_Fuel] Equation2.63 Unit: kgCO2/Liter

Documentation: This is the amount of CO2 in kg released per litre of fuel burnt. Biofuel has a large variety of fuels and thus, has different CO2 emissions (New Zealand Government 2019; Llewellyn & Miftakhov 2022; Yoo et al 2022; De Joing 2017; Ballal 2023).
Name: CO2_released_per_Unit_of_Usage[Hydrogen] Equation: 0
Name: CO2_released_per_Unit_of_Usage[efuels] Equation: 2.63*0.1
Name: CO2_released_per_Unit_of_Usage[Biofuel] Equation: IF "POLICY_SWITCH_-_Biofuel_Production_Selection"=0 THEN 2.63*0.1 ELSE 2.63*0
Name: Comparative_Fuel_Production[Norway, Traditional_Aviation_Fuel] Equation: TAF_Feedstock Unit: dmnl Documentation: This variables function is to re add TAF into the array and set up the future graphical function hence, the two different equations. TAF feedstock is set to 1 since we assume the production is always possible. The other fuels compare fuels able to be produced to the reference production TAF.
Name: Comparative_Fuel_Production[Norway, Hydrogen] Equation: Fuel_able_to_be_produced[Norway,Hydrogen]//Reference_Production_TAF[Norway]
Name: Comparative_Fuel_Production[Norway, efuels] Equation: Fuel_able_to_be_produced[Norway,efuels]//Reference_Production_TAF[Norway]
Name: Comparative_Fuel_Production[Norway, Biofuel] Equation Fuel_able_to_be_produced[Norway,Biofuel]//Reference_Production_TAF[Norway]
Name: Comparative_Fuel_Production[Sweden, Traditional_Aviation_Fuel] Equation: TAF_Feedstock
Name: Comparative_Fuel_Production[Sweden, Hydrogen] Equation: Fuel_able_to_be_produced[Sweden,Hydrogen]//Reference_Production_TAF[Sweden]
Name: Comparative_Fuel_Production[Sweden, efuels] Equation: Fuel_able_to_be_produced[Sweden,efuels]//Reference_Production_TAF[Sweden]
Name: Comparative_Fuel_Production[Sweden, Biofuel] Equation: Fuel_able_to_be_produced[Sweden,Biofuel]//Reference_Production_TAF[Sweden]
Name: Comparative_Fuel_Production[Denmark, Traditional_Aviation_Fuel] Equation: TAF_Feedstock
Name: Comparative_Fuel_Production[Denmark, Hydrogen] Equation: Fuel_able_to_be_produced[Denmark,Hydrogen]//Reference_Production_TAF[Denmark]

Name: Comparative_Fuel_Production[Denmark, efuels] Equation: Fuel_able_to_be_produced[Denmark,efuels]//Reference_Production_TAF[Denmark]
Name: Comparative_Fuel_Production[Denmark, Biofuel] Equation: Fuel_able_to_be_produced[Denmark,Biofuel]//Reference_Production_TAF[Denmark]
Name: Cost_of_Constructing_to_meet_Demand[Norway, Traditional_Aviation_Fuel] Equation: (Storage_Requirement_per_Fuel[Norway,Traditional_Aviation_Fuel]-TAF_and_Drop_in_Storage_Capacity[Norway])*Cost_of_Construction[Norway,Traditional_Aviation_Fuel] Unit: US Dollars Documentation: This variable is the amount of USD it will cost to construct the storage that will be needed to meet 100% of demand. It will be calculating the cost of the total. So, if there is a large amount of storage missing (there is no storage constructed) then this will be large as the price is high. If the fuel is equal to the demand, then the costs will be small.
Name: Cost_of_Constructing_to_meet_Demand[Norway, Hydrogen] Equation: (Storage_Requirement_per_Fuel[Norway,Hydrogen]-Hydrogen_Storage_Capacity[Norway])*Cost_of_Construction[Norway,Hydrogen]
Name: Cost_of_Constructing_to_meet_Demand[Norway, efuels] Equation: (Storage_Requirement_per_Fuel[Norway,efuels]-TAF_and_Drop_in_Storage_Capacity[Norway])*Cost_of_Construction[Norway,efuels]
Name: Cost_of_Constructing_to_meet_Demand[Norway, Biofuel] Equation: (Storage_Requirement_per_Fuel[Norway,Biofuel]-TAF_and_Drop_in_Storage_Capacity[Norway])*Cost_of_Construction[Norway,Biofuel]
Name: Cost_of_Constructing_to_meet_Demand[Sweden, Traditional_Aviation_Fuel] Equation(Storage_Requirement_per_Fuel[Sweden,Traditional_Aviation_Fuel]-TAF_and_Drop_in_Storage_Capacity[Sweden])*Cost_of_Construction[Sweden,Traditional_Aviation_Fuel]
Name: Cost_of_Constructing_to_meet_Demand[Sweden, Hydrogen] Equation: (Storage_Requirement_per_Fuel[Sweden,Hydrogen]-Hydrogen_Storage_Capacity[Sweden])*Cost_of_Construction[Sweden,Hydrogen]
Name: Cost_of_Constructing_to_meet_Demand[Sweden, efuels] Equation: (Storage_Requirement_per_Fuel[Sweden,efuels]-TAF_and_Drop_in_Storage_Capacity[Sweden])*Cost_of_Construction[Sweden,efuels]
Name: Cost_of_Constructing_to_meet_Demand[Sweden, Biofuel] Equation: (Storage_Requirement_per_Fuel[Sweden,Biofuel]-TAF_and_Drop_in_Storage_Capacity[Sweden])*Cost_of_Construction[Sweden,Biofuel]
Name: Cost_of_Constructing_to_meet_Demand[Denmark, Traditional_Aviation_Fuel] Equation:(Storage_Requirement_per_Fuel[Denmark,Traditional_Aviation_Fuel]-TAF_and_Drop_in_Storage_Capacity[Denmark])*Cost_of_Construction[Denmark,Traditional_Aviation_Fuel]
Name: Cost_of_Constructing_to_meet_Demand[Denmark, Hydrogen]

Equation: (Storage_Requirement_per_Fuel[Denmark,Hydrogen]- Hydrogen_Storage_Capacity[Norway])*Cost_of_Construction[Norway,Hydrogen]
Name: Cost_of_Constructing_to_meet_Demand[Denmark, efuels] Equation: (Storage_Requirement_per_Fuel[Denmark,efuels]- TAF_and_Drop_in_Storage_Capacity[Denmark])*Cost_of_Construction[Denmark,efuels]
Name: Cost_of_Constructing_to_meet_Demand[Denmark, Biofuel] Equation: (Storage_Requirement_per_Fuel[Denmark,Biofuel]- TAF_and_Drop_in_Storage_Capacity[Denmark])*Cost_of_Construction[Denmark,Biofuel]
Name: Cost_of_Construction[Country, Fuel] Equation: Initial_Investment_Cost*Effect_of_Existing_TAF_and_Drop_in_Infrastructure_on_Fuel_ Mix Unit: USD/Kilogram Documentation: This is the cost per kg of storage. It takes the normal investment cost per kg and multiplies it with the effect that will either increase or decrease costs.
Name: Cost_of_Energy[Country, Fuel] Equation:((Storage_Requirement_per_Fuel)*Price_per_Fuel) Unit: USD Documentation: This is the cost of energy which represents the total cost that would be needed to pay to meet demand with each fuel. So, if the demand is 100% hydrogen, then how much would it cost to get that amount of hydrogen. The variable does this calculation for every fuel to see how expensive or cheap it would be per fuel.
Name: Days_in_a_Year Equation: 365 Unit: Days/Year Documentation: This is the amount of days in a year as we need it to figure out how many flights per year a plane can do.
Name: Desired_Planes[Country, Flights] Equation: Aviation_Demand_Trips/Maximm_Trips_per_Type_of_Flight[Flights] Unit: Plane Documentation: Dividing the total flights demand by the maximum amount of maximum possible trips in a year per plane gives the number of planes that the airline companies need to meet the demand. The model only deals with departures as if arrivals were included in the model, it would double count a lot of the flights as majority of the trips are short haul. Short haul flights include any flight in Scandinavia so if we counted arrivals and departures, a flight between Oslo and Copenhagen would be counted twice.
Name: Desired_Share_of_Fuel_Mix[Country, Fuel] Equation: SMTH1(Share_of_Investment, Setting_Fuel_Strategy_Time, Initial_Shares_of_Fuel_Mix[Fuel]) Unit: dmnl

Documentation: This delay converter takes the input share of investment and puts it into SMTH3 function to represent the slow decision to start investing into the specific fuel. This information delay is the long meetings that the executives take and slowly decide which fuel to take. The reason it is a SMTH3 delay converter is to represent the multiply information delay present in larger organizations. DELAY CONVERTER
Name: Desired_Storage[Country, Fuel](t) Equation: Desired_Storage[Country, Fuel](t - dt) + (Change_in_Desired_Storage[Country, Fuel]) * dt INIT Desired_Storage[Country, Fuel] = Indicated_Desired_Storage Unit: Kilograms Documentation: This is the stock of desired storage which is an information delay from the indicated desired storage. It increases or decreases via the biflow of change in desired storage which goes negative if the stock is larger than the indicated and goes positive if the opposite is true. This is a stock as it represents the delay in getting the new plans for storage for fuels set up and audited. In addition, it also factors in the incremental approach to transitions that companies are prone to taking.
Name: Effect_of_Biofuel_on_Demand_Through_Price[Country] Equation: GRAPH(Actual_Share_of_Fuel_Mix[Country,Biofuel]//HISTORY(Actual_Share_of_Fuel_Mix[Country,Biofuel], TIME-2)) Points: (1.000, 1.0000), (1.100, 0.9981), (1.200, 0.9935), (1.300, 0.9825), (1.400, 0.9599), (1.500, 0.9250), (1.600, 0.8901), (1.700, 0.8675), (1.800, 0.8565), (1.900, 0.8519), (2.000, 0.8500) Unit: dmnl Documentation: This effect compares the share of the fuel mix that consists of biofuel compared to the fuel mix 2 years ago. This is to represent the fact that switching to the new fuels will be expensive initially before the new price spikes become the norm. If the fuel mix has not changed than it is equal to 1 meaning, there is no effect. If the fuel mix has increased since 2 years ago the effect will start to decrease towards a maximum of 0.85 representing the customers that stop flying since the change in price caused by shifting fuels is perceived to be too expensive for them. If the fuel mix is less than it was 2 years ago it will only increase to maximum of 1 meaning it cannot increase demand as it becomes cheaper.
Name: Effect_of_Demand_on_Price[Country, Fuel] Equation: GRAPH(Actual_Share_of_Fuel_Mix) Points: (0.000, 1.0000), (0.100, 1.0200), (0.200, 1.0400), (0.300, 1.0600), (0.400, 1.0800), (0.500, 1.1000), (0.600, 1.1200), (0.700, 1.1400), (0.800, 1.1600), (0.900, 1.1800), (1.000, 1.2000) Unit: dmnl Documentation: This is the effect of demand on the price of fuel. It is a graphical function that either increase or decreases the price depending on the input. The input is the actual share of fuel mix which goes from 0 to 1 (0-100% of the fuel mix). If the fuel mix for a specific fuel is 1 then it is high demand and will thus increase the price to a maximum of 1.2. If the actual fuel share if equal to 0 then the effect will be 1 meaning, there is no effect

on the price. This is because if the demand was 0 and the effect went below 1 then it would decrease the price which would make it even cheaper.
Name: Effect_of_Efuels_on_Demand_Through_Price[Country] Equation: GRAPH(Actual_Share_of_Fuel_Mix[Country,efuels]//HISTORY(Actual_Share_of_Fuel_Mix[Country,efuels], TIME-2)) Points: (1.000, 1.0000), (1.100, 0.9981), (1.200, 0.9935), (1.300, 0.9825), (1.400, 0.9599), (1.500, 0.9250), (1.600, 0.8901), (1.700, 0.8675), (1.800, 0.8565), (1.900, 0.8519), (2.000, 0.8500) Unit: dmnl Documentation: This effect compares the share of the fuel mix that consists of e-fuels compared to the fuel mix 2 years ago. This is to represent the fact that switching to the new fuels will be expensive initially before the new price spikes become the norm. If the fuel mix has not changed than it is equal to 1 meaning, there is no effect. If the fuel mix has increased in the last 2 years ago the effect will start to decrease towards a maximum of 0.85 representing the customers that stop flying since the change in price caused by shifting fuels is perceived to be too expensive for them. If the fuel mix is less than it was 2 years ago it will only increase to maximum of 1 meaning it cannot increase demand as it becomes cheaper.
Name: Effect_of_Existing_TAF_and_Drop_in_Infrastructure_on_Fuel_Mix[Country, Fuel] Equation: GRAPH(level_of_TAF_and_Drop_in_Compatible_Infrastructure) Points: (0.000, 1.700), (0.200, 1.682), (0.400, 1.639), (0.600, 1.537), (0.800, 1.325), (1.000, 1.000), (1.200, 0.6746), (1.400, 0.4631), (1.600, 0.3608), (1.800, 0.3177), (2.000, 0.300) Unit: dmnl Documentation: This graphical function takes the economies of scale comparison for the storage functions and give the output of a effect in the selected range. The effect variable represents the effect that having storage can mean on costs, in building rapport with companies and having already covered the initial expensive investment costs. If the input is equal to 1 then the output of the function is 1. If the input is larger than 1 than the graphical function will decrease its output to a minimum of 0.3 meaning, there price will be 30% of the original price. If the input is smaller than 1 than the price increases towards a maximum of 1.7 which means it will be 70% more expensive than the normal price.
Name: Effect_of_Hydrogen_Share_on_Demand_Through_Price[Country] Equation: GRAPH(Actual_Share_of_Fuel_Mix[Country,Hydrogen]//HISTORY(Actual_Share_of_Fuel_Mix[Country,Hydrogen], TIME-2)) Points: (1.000, 1.0000), (1.100, 0.9968), (1.200, 0.9891), (1.300, 0.9709), (1.400, 0.9331), (1.500, 0.8750), (1.600, 0.8169), (1.700, 0.7791), (1.800, 0.7609), (1.900, 0.7532), (2.000, 0.7500) Unit: dmnl Documentation: This effect compares the share of the fuel mix that consists of hydrogen compared to the fuel mix 2 years ago. This is to represent the fact that switching to the new fuels will be expensive initially before the new price spikes become the norm. If the fuel mix has not changed than it is equal to 1 meaning, there is no effect. If the fuel mix has increased since 2 years ago the effect will start to decrease towards a

maximum of 0.75 representing the customers that stop flying since the change in price caused by shifting fuels is perceived to be too expensive for them. If the fuel mix is less than it was 2 years ago it will only increase to maximum of 1 meaning it cannot increase demand as it becomes cheaper.
Name: Emissions[Country] Equation: Total_Emissions/Annual_Emissions Unit: TonnesCO2/Years Documentation: This inflow increases the accumulated CO2 pollution. It represents the emissions that are coming from the fuel burning part of the aviation industry. Its intake is the Total emissions measured in TonnesCO2 over the delay of 1 year to show the annual emissions.
Name: Emissions_from_Fuel_Usage[Country, Fuel] Equation: ((Storage_Requirement_per_Fuel/"Kg/Liter"[Fuel])*Actual_Share_of_Fuel_Mix)*CO2_released_per_Unit_of_Usage[Fuel] Unit: kgCO2 Documentation: This is the amount of CO2 released per fuel. It takes the fuel demand and multiply it with the CO2 released per unit of fuel. If the demand for fuel is 0 then it does not release any CO2 from said fuel. If the CO2 released per unit is 0, ie, the fuel is carbon neutral then again, the CO2 emissions are 0. Since the demand for aviation fuel is measured in kg it needs to be first converted into litres and then turned into CO2.
Name: Energy_Content[Traditional_Aviation_Fuel] Equation: 42.8 Unit: MJ/kg Documentation: The energy content or specific energy is the amount of energy that exists within a kg of fuel. If a vehicle requires 1 MJ of energy to drive a km and there is 1MJ in kg of fuel then it would use up (without considering any other factors such as weight, pre-existing movement, and other engineering aspects) then it would use up 1 kg of fuel within that time. The following energy content was found: The energy content for TAF was taken from Ministry of Defense (2019). The biofuel energy content was found by Herrell (2022) and Li (2021). The e-fuel energy content was calculated by Gofman (2003). The hydrogen energy content was found by the EERE (2022) and These specifications fit the aviation fuel standards as set by the Ministry of Defense (2019).
Name: Energy_Content[Hydrogen] Equation:120
Name: Energy_Content[efuels] Equation: 42.8
Name: Energy_Content[Biofuel] Equation: IF "POLICY_SWITCH_-_Biofuel_Production_Selection"= 0 THEN 43.7 ELSE IF "POLICY_SWITCH_-_Biofuel_Production_Selection"=1 THEN 43.2 ELSE 43.2
Name: Energy_Efficiency Equation: 464.7255

Unit: MJ/km Documentation: The energy efficiency if the amount of energy used up per kilometre of flight. It is important to note that this is not e specific number but a large set of calculations depending on weight, take-off, wind conditions and much more. So, the number is not the whole picture but close enough. The number was calculated by using the same step as found in the source (Aiimpacts 2023).
Name: "EOS_-_Storage_Tanks"[Norway, Traditional_Aviation_Fuel] Equation: 10e7 Unit: Kilograms Documentation: This is the threshold for economics of scale effects to kick in. The value was calibrated, and sensitivity tested.
Name: “EOS_-_Storage_Tanks"[Norway, Hydrogen] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Norway, efuels] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Norway, Biofuel] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Sweden, Traditional_Aviation_Fuel] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Sweden, Hydrogen] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Sweden, efuels] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Sweden, Biofuel] Equation: 10e7
Name:"EOS_-_Storage_Tanks"[Denmark, Traditional_Aviation_Fuel] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Denmark, Hydrogen] Equation: 10e7
"Name: EOS_-_Storage_Tanks"[Denmark, efuels] Equation: 10e7
Name: "EOS_-_Storage_Tanks"[Denmark, Biofuel] Equation: 10e7
Name: Fleet[Country, Flights](t) Equation: Fleet[Country, Flights](t - dt) + (Purchasing_of_Planes[Country, Flights] - Plane_Lifecycle[Country, Flights]) * dt INIT Fleet[Country, Flights] = Desired_Planes Unit: Plane Documentation: The stock of fleet is arrayed by the category of flights (short, medium, and long) and by country. It increases through the flow purchasing of planes and the outflow of

plane lifecycle. The fleet represents the total planes present in each country's total fleet. It is not a specific company but rather the total fleets in each country.
Name: Forecasting_Demand Equation: 1.5 Unit: years Documentation: The model assumes that the airport wants to have a safety net of aviation fuel around in case there is sudden increase in flights. The model assumes that to be 1.5 years demand as any larger than that would make the upkeep costs too large, and aviation is not a volatile field.
Name. Hydrogen_Plane_Lifecycle[Country, Flights] Equation: Hydrogen_Planes/Plane_Lifetime Unit: Plane/Years Documentation: This flow decreases the stock of hydrogen planes. The equation is the stock divided by the resident time which is equal to the same as the original planes. The plane lifetime is assumed to be same as the one for original plane as it is hard to calculate said lifetime for a product that is very scarce and not ready for the market.
Name. Hydrogen_Planes[Country, Flights](t) Equation: Hydrogen_Planes[Country, Flights](t - dt) + (Ordering_of_New_Hydrogen_Planes[Country, Flights] - Hydrogen_Plane_Lifecycle[Country, Flights]) * dt INIT Hydrogen_Planes[Country, Flights] = 0 Unit: Plane Documentation: The stock of hydrogen planes is a co-flow structure that takes the flow into the total fleet and displays the share of that fleet being hydrogen. It will not go above the size of the fleet stock and at most can be equal to it which would then represent the entire fleet being full of hydrogen planes. It increases through the flow of 'Ordering new Hydrogen Planes' and decreases through the 'Hydrogen Plane Lifecycle'. The plane lifetime is assumed to be same as the one for original plane as it is hard to calculate said lifetime for a product that is very scarce and not ready for the market.
Name: Indicated_Desired_Storage[Country, Fuel] Equation: (Storage_Requirement_per_Fuel*Desired_Share_of_Fuel_Mix) Unit: Kilograms Documentation: This is the indicated desired storage so it represents the actual investments before they occur. If this shows that hydrogen storage is a good investment, then it goes at that moment good but because of the delay in companies moving the airports will not invest into before that information has been true for a while. The equation takes the demand translated into all the types of fuel and sees if what desired share of that needs to be take per fuel. If 20% of the fuel mix should be hydrogen it will take 20% of the total energy demand of hydrogen.
Name: Initial_Effect Equation: 1

Unit: dmnl Docuemntation: This is the initial effect of the price. It is set as 1 as that is the relative price in 1980. Relative price is what the price is compared to what it was last year. so if it is 1.2 it is 20% more expensive than last year.
Name: Initial_Investment_Cost[Norway, Traditional_Aviation_Fuel] Equation: 0.67 Unit: USD/Kilogram Documentation: This represents the cost of 1kg of fuel storage. For hydrogen fuel storage it is assumed that one needs 700 bars of pressure which according to Tzimas et al (2003) would then cost 3200 USD per litre which if divided by 14 (conversion rate to kg) would mean it would cost 228 USD per kg. Since TAF and drop-infuels use the same storage, they would all cost the same as there would be no need for a storage transition. The type of storage was assumed to be the larges tanks available which is the Grande 68v which can hold 50000 litres (Unityfuel 2023). Converting Jet A1 to kg from litres makes the storage tank hold 40000 kg. A price of such a thing was found on to be 27000 USD on large online retailers such as 39. Luqiang Energy Equipment Co., Ltd (No Date available). Thus, to find the cost per kg of fuel we divide the price with the storage gives this formulation: - Average price 27000 // 40000 kg = 0.67 USD/kg
Name: Initial_Investment_Cost[Norway, Hydrogen] Equation: 228.57 {3200
Name: Initial_Investment_Cost[Norway, efuels] Equation: 0.67
Name: Initial_Investment_Cost[Norway, Biofuel] Equation: 0.67
Name: Initial_Investment_Cost[Sweden, Traditional_Aviation_Fuel] Equation: 0.67
Name: Initial_Investment_Cost[Sweden, Hydrogen] Equation: 228.57 {3200
Name: Initial_Investment_Cost[Sweden, efuels] Equation: 0.67
Name: Initial_Investment_Cost[Sweden, Biofuel] Equation: 0.67
Name: Initial_Investment_Cost[Denmark, Traditional_Aviation_Fuel] Equation: 0.67
Name: Initial_Investment_Cost[Denmark, Hydrogen] Equation: 228.57 {3200
Name: Initial_Investment_Cost[Denmark, efuels] Equation: 0.67
Name: Initial_Investment_Cost[Denmark, Biofuel] Equation: 0.67
Name. Initial_Shares_of_Fuel_Mix[Traditional_Aviation_Fuel] Equation: 1

Unit: dmnl Documentation: This is the initial share of fuel mix for the delay converter that sets the desired share of fuel mix.
Name: Initial_Shares_of_Fuel_Mix[Hydrogen] Equation: 0
Name: Initial_Shares_of_Fuel_Mix[efuels] Equation: 0
Name: Initial_Shares_of_Fuel_Mix[Biofuel] Equation: 0
Name: Kg_to_Tonnes Equation: 0.001 Unit: TonnesCO2/KgCO2 Documentation: This is the conversion multiplier from going to tonnes by kilograms.
Name: "Kg/Liter"[Traditional_Aviation_Fuel] Equation: 0.85 Unit: Kg/Liter Documentation: This is the conversion from kg to litre. It is different from hydrogen as it is a much lighter fuel compared to the others.
Name: "Kg/Liter"[Hydrogen] Equation: 0.0045
Name: "Kg/Liter"[efuels] Equation: 0.85
Name: "Kg/Liter"[Biofuel] Equation: 0.85
Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Norway, Equation:Traditional_Aviation_Fuel] Equation: TAF_and_Drop_in_Storage_Capacity[Norway]//"EOS_- _Storage_Tanks"[Norway,Traditional_Aviation_Fuel] Unit: dmnl Documentation: This variable does two things. 1) it re-arrays the fuels to simplify the structure and 2) it compares the current storage to the economies of scale threshold of storage tanks. If the storage tanks are larger than the threshold, then this variable goes above 1. If it is below the threshold, then this variable is below 1.
Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Norway, Hydrogen] Equation: Hydrogen_Storage_Capacity[Norway]//"EOS_- _Storage_Tanks"[Norway,Hydrogen]
Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Norway, efuels] Equation: TAF_and_Drop_in_Storage_Capacity[Norway]//"EOS_- _Storage_Tanks"[Norway,efuels]
Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Norway, Biofuel]

Equation: TAF_and_Drop_in_Storage_Capacity[Norway]//"EOS_-_Storage_Tanks"[Norway,Biofuel]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Sweden, Traditional_Aviation_Fuel]
Equation: TAF_and_Drop_in_Storage_Capacity[Sweden]//"EOS_-_Storage_Tanks"[Sweden,Traditional_Aviation_Fuel]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Sweden, Hydrogen]
Equation: Hydrogen_Storage_Capacity[Sweden]//"EOS_-_Storage_Tanks"[Sweden,Hydrogen]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Sweden, efuels]
Equation: TAF_and_Drop_in_Storage_Capacity[Sweden]//"EOS_-_Storage_Tanks"[Sweden,efuels]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Sweden, Biofuel]
Equation: TAF_and_Drop_in_Storage_Capacity[Sweden]//"EOS_-_Storage_Tanks"[Sweden,Biofuel]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Denmark, Traditional_Aviation_Fuel]
Equation: TAF_and_Drop_in_Storage_Capacity[Sweden]//"EOS_-_Storage_Tanks"[Denmark,Traditional_Aviation_Fuel]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Denmark, Hydrogen]
Equation: Hydrogen_Storage_Capacity[Denmark]//"EOS_-_Storage_Tanks"[Denmark,Hydrogen]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Denmark, efuels]
Equation: TAF_and_Drop_in_Storage_Capacity[Denmark]//"EOS_-_Storage_Tanks"[Denmark,efuels]

Name: level_of_TAF_and_Drop_in_Compatible_Infrastructure[Denmark, Biofuel]
Equation: TAF_and_Drop_in_Storage_Capacity[Denmark]//"EOS_-_Storage_Tanks"[Denmark,Biofuel]

Name: Maximm_Trips_per_Type_of_Flight[Flights]
Equation: Maximum_Trips_in_a_Day*Days_in_a_Year

Unit: Flights/Plane/Year
Documentation: Multiplying the maximum trips possible per category of plane per day with the days in a year we can find the maximum trips per plane per year.

Name: Maximum_Trips_in_a_Day[Short_Haul]
Equation: 11

Unit: Flights/Plane/Day
Documentation: The maximum amount of trips in a day are calculated based on the median value of the flight and then multiplied up to the maximum active flight time during a day. Airports are closed usually between 6 and midnight which leaves around 18 hours for possible trips hence, that is the goal. The category of flights can be divided into time (hour) categories as well where the cut up off points are:

Short<3<Medium<6<Long

So taking the median hour is 1.5 for short and 5 for medium. For Long flights the longest flight in Scandinavia was used as the longest trip. The longest trip is the 12-hour flight from Copenhagen to San Francisco. That means the median trip is 9 hours. The following calculations were done to find how many trips per day: 9*8= 72 hours 72 hours = 3 days 8 Trips in 72 Hours 8/3 days -> 2.6666 Trips per day and then rounded down to 2.5 trips per day. The median short haul flight is 1.5 hours and if we account for no time between departures, it becomes 10 trips per day. The median medium haul flight is 4.5 hours so if we account for no time between departures it becomes 4 trips per day.
Name: Maximum_Trips_in_a_Day[Medium_Haul] Equation: 4
Name: Maximum_Trips_in_a_Day[Long_Haul] Equation: 2.5
Name: Ordering_of_New_Hydrogen_Planes[Country, Flights] Equation: Purchasing_of_Planes*Share_of_Planes_Being_Hydrogen Unit: Plane/Years Documentation: This flow takes the flow of purchasing planes and multiplied it with the share of those planes being hydrogen planes. If the share of planes being hydrogen increases, then the stock of hydrogen planes will be larger to the maximum of being the same size as the original fleet stock.
Name: Plane_Lifecycle[Country, Flights] Equation: Fleet/Plane_Lifetime Unit: Plane/Years Documentation: This is the outflow of stock of the fleet. It represents the end of the lifetime of the planes in the fleet which is on average 22-30 years. The stated lifetime of a plane is 30 years but, they are often replaced after 22 years hence, the range. If the fleet is 0 then it will not be depleted as there is no planes left.
Name: Plane_Lifetime Equation: 18 Unit: Year Documentation: The plane lifetime is based on a range and then tested. The range is based on what occurs and what the biggest airplane producers stated total lifetime. Airbus states that the lifetime of a plane is roughly 30 years which thus, gives the largest lifetime (Airbus 2023). The service of a plane remains around 18 years based on the findings of plane enthusiasts (Planespotters 2023).
Name: Possible_Flights_per_Year[Country, Flights] Equation: Fleet*Maximm_Trips_per_Type_of_Flight[Flights]

Unit: Flights/Year Documentation: By multiplying the fleet by the maximum trips possible per plane in a year gives the total trips possible based on the actual fleet. So instead of being demand this is the usage, or rather the actual number of flights that occur after demand.
Name: Price_per_Fuel[Norway, Traditional_Aviation_Fuel] Equation: MAX(TAF_Price+TESTING, 0.005) Unit: USD/Kilogram Documentation: These variable re-arrays the fuels into the same structure by re adding the TAF price with the rest of the fuels.
Name: Price_per_Fuel[Norway, Hydrogen] Equation: PRICE[Norway,Hydrogen]
Name: Price_per_Fuel[Norway, efuels] Equation: PRICE[Norway,efuels]
Name: Price_per_Fuel[Norway, Biofuel] Equation: PRICE[Norway,Biofuel]
Name: Price_per_Fuel[Sweden, Traditional_Aviation_Fuel] Equation: MAX(TAF_Price+TESTING, 0.005)
Name: Price_per_Fuel[Sweden, Hydrogen] Equation: PRICE[Sweden,Hydrogen]
Name: Price_per_Fuel[Sweden, efuels] Equation: PRICE[Sweden,efuels]
Name: Price_per_Fuel[Sweden, Biofuel] Equation: PRICE[Sweden,Biofuel]
Name: Price_per_Fuel[Denmark, Traditional_Aviation_Fuel] Equation: MAX(TAF_Price+TESTING, 0.005)
Name: Price_per_Fuel[Denmark, Hydrogen] Equation: PRICE[Denmark,Hydrogen]
Name: Price_per_Fuel[Denmark, efuels] Equation: PRICE[Denmark,efuels]
Name: Price_per_Fuel[Denmark, Biofuel] Equation: PRICE[Denmark,Biofuel]
Name: Purchasing_of_Planes[Country, Flights] Equation: (Desired_Planes-Fleet)/Time_to_Order_new_Planes Unit: Plane/Years Documentation: The flow represents the airline companies purchasing new planes to meet demand. The equation is a goal-gap formation as it is not the main part of the model, so it was kept as simple as possible. If desired planes increase, then the stock of fleet increases by the same amount with a delay of 5 years it takes to order or wet lease the planes.
Name: Setting_Fuel_Strategy_Time Equation: 5

Unit: Years Documentation: This is the perception delay in setting the desired share of fuel mix. It is set to 5 years as the companies need to consider every aspect of the supply chain and decisions before deciding to invest into the specific fuels.
Name: Share_of_Fleet_being_Hydrogen_Planes[Country] Equation: SUM(Hydrogen_Planes[Country,*])//Total_Fleet_Size Unit: dmnl Documentation: This variable compares the amount of hydrogen planes to the total fleet size to see what percentage of the fleet consists of hydrogen. If this is equal to 1 then 100% of the fleet is hydrogen.
Name: Share_of_Orders_Being_Hydrogen[Country] Equation: Ordered_Hydrogen_Tanks//Total_New_Orders Unit: dmnl Documentation: By dividing the stock of Ordered Hydrogen Tanks by the total orders we find the share of new orders being hydrogen. This is done to inform the airline markets about what share of new planes that they buy should be hydrogen-based planes.
Name: Share_of_Planes_Being_Hydrogen[Country, Flights] Equation: DELAY3(Share_of_Orders_Being_Hydrogen[Country], Time_to_Acquire_Hydrogen_Planes[Flights]) Unit: dmnl Documentation: This is the share of planes being hydrogen planes. It goes from 0 to 1 as percentage. 1 being 100% and 0 being none of the planes. It is a delay3 function to represent the process of ordering and constructing the planes. DELAY CONVERTER
Name: Share_of_Seat_Demand_per_Type_of_Flight[Short_Haul] Equation: 0.6 Unit: dmnl/year Documentation: The model splits the demand into three categories as used by the EU; Short haul, medium haul, and long haul. The share is based on the authors own observation, calibration, and sensitivity analysis. The initial shares are: Short Haul: 0.6 Medium Haul: 0.3 Long Haul: 0.1
Name: Share_of_Seat_Demand_per_Type_of_Flight[Medium_Haul] Equation: 0.3
Name: Share_of_Seat_Demand_per_Type_of_Flight[Long_Haul] Equation: 0.1
Name: Storage_needed_for_TAF_and_Drop_in_Fuels[Country] Equation: Desired_Storage[Country,Traditional_Aviation_Fuel]+Desired_Storage[Country,efuels]+Desired_Storage[Country,Biofuel]

Unit: Kilograms Documentation: This is the desired level of storage for TAF and Drop-in fuels. Since all three can use the same infrastructure, they are removed from the array and separated into their own material delay structure.
Name: Storage_Requirement_per_Fuel[Country, Fuel] Equation: (Total_Civil_Aviation_Demand[Country]//(Energy_Content[Fuel]))*Forecasting_Demand Unit: Kilograms Documentation: This is the energy demand for aviation fuel calculated into each fuel type in kilograms. It divides the energy demand per the energy content per fuel to see how much fuel in kg would be needed to meet the total energy demand and then increase it by 1.5 so that the airports keep an additional amount of fuel around in case of emergencies.
Name: TAF_Feedstock Equation: 1 Unit: dmnl Documentation: Traditional aviation fuel (TAF) can run out eventually as the chemicals and oil that is needed to make jet fuel is not endless however, for the purpose of this model we are assuming that if there is not enough production of SAF then the company would stick to the TAF hence, the feed stock being 1 as it represents it can produce as much as possible.
Name: Time_to_Acquire_Hydrogen_Planes[Short_Haul] Equation: 7 Unit: Years Documentation: This is the time it takes for the share of planes being hydrogen to increase. It is based on the cycle of models for planes. An airbus c-suite executive mentioned in a Rystad Energy Talk (2023) that it takes around 7 years to go from drawing to market. Hence, the category of flights increasing by 7 as it is assumed that short flights would the first to enter the market, and then working up towards long haul flights.
Name: Time_to_Acquire_Hydrogen_Planes[Medium_Haul] Equation: 14
Name: Time_to_Acquire_Hydrogen_Planes[Long_Haul] Equation: 21
Name: Time_to_Order_new_Planes Equation: 5 Unit: Years Documentation: This is the time it takes for a airline company to order a plane either through full purchase or commonly a wet lease. Hence, it being shorter than the construction time of a plane.
Name: Time_to_update_Desired_Storage Equation: 10 Unit: Years

Documentation: This is the time it takes to update the desired storage per fuel. It is set to 5 years to show the slowness in markets to adapt to new technology.
Name: Time_to_Update_Perceived_price Equation: 1 Unit: Year Documentation: This is the time it takes for the public to perceive the updates on price. It is set to 1 year as the people compare price to what they were a year ago. If one was to buy tickets to travel back for the summer, as they do every year, then the reference value would be what the price was a year ago.
Name: Total_Civil_Aviation_Demand[Country] Equation: SUM(Aviation_Energy_Demand_per_Type_of_Flight[Country,*]) Unit: MJ/Year Documentation: This sums up the total energy demand per type of flight in each of the three countries to find the total energy demand in any of the three countries.
Name: Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Country] Equation: SMTH3(Effect_of_Hydrogen_Share_on_Demand_Through_Price*Effect_of_Biofuel_on_Demand_Through_Price*Effect_of_Efuels_on_Demand_Through_Price,Time_to_Update_Perceived_price, Initial_Effect) Unit: dmnl Documentation: This delay converter represents the price that the general populace perceives and thus, adjusts their air travel demand according to that perception. It multiplies the effect of biofuel, hydrogen, and e-fuels on price. This means that if the fuel mix has not changed recently, this variable is equal to 1 as there is no recent changes in the mix meaning that the perception of the populace is that its just as cheap or expensive as it was 2 years ago. DELAY CONVERTER
Name: Total_Emissions[Country] Equation: SUM(Emissions_from_Fuel_Usage[Country,*])*Kg_to_Tonnes Unit: TonnesCO2 Documentation: This is the total emissions from fuel usage in the aviation industry. It uses the sum function to collect all the arrayed fuels into one variable before multiplying it with kg to tonnes to convert into the Tonnes of CO2.
Name. Total_Flights[Country] Equation: SUM(Aviation_Demand_Trips[Country,*]) Unit: Flights/Year Documentation: This sums demand for flights per country as to show the total demand for flights instead of the demand for each category.
Name: Total_New_Orders[Country] Equation Ordered_TAF_and_Drop_in_TAnks+Ordered_Hydrogen_Tanks Unit: Kilograms

Documentation: Adding the two types of infrastructure together gives the total orders coming in. This is done to find the total orders places to eventually find the new orders being for hydrogen infrastructure.
CLD.Air_Travel_Demand NAN(Perceived_Ticket_Price,GDP_Pc,Population) DELAY CONVERTER
Aviation Demand:
Name: Air_Travel_Demand[Country] Equation: (Population_Measured_in_Seats*Flight_per_Person)*Remaining_Share_preferring_Aviation*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price Unit: Seats Documentation: Air travel demand can be simplified as the flights per person multiplied together with the population measured in seats. In other words, the demand for airplane seats. The effect variables come from people willing to travel on alternative transports and the effect that price has on demand. So, if more people are willing to travel via alternative routes than airplane seat demand decreases. If price increase than some people are less willing to travel via plane as it is perceived to be expensive.
Name: Aviation_Market_Growth[Country] Equation: TREND(Air_Travel_Demand, 10) Unit: dmnl/year Documentation: This calculates the growth per year of seat demand. This is then compared to the Eurocontrol (2018) report to see if it the growth is realistic.
Name: Effect_of_GDP_pc_on_Flight_pc[Country] Equation: GDP_pc/INIT(GDP_pc) Unit: dmnl Documentation: The effect of GDP pc on Flight pc is GDP pc divided by the initial value of GDP pc in 1980. To use an elasticity formulation, one needs to divide the effect by its initial to isolate the increase that occurs from time 1 to end time. This part of the equation is sorted out of the next part to clearer be able to demonstrate the steps in the equation.
Name: Elasticity_of_GDP_pc_to_Flights_per_Person Equation: 1.31 Unit: dmnl Documentation: The elasticity of GDP pc to Flights per person is how much change an increase/decrease in GDP pc results in changes in Flights per person. Since the elasticity is equal to 1.31 it means that for every 1 unit increase in GDP pc, flights per person increase by 1.31. This elasticity was provided by DNV (DNV 2023).
Name: Flight_per_Person[Country] Equation: Regional_Adjustment_Factor*Effect_of_GDP_pc_on_Flight_pc^Elasticity_of_GDP_pc_to_Flights_per_Person

Unit: dmnl Equation: The equation 'regional factor*GDP pc^Elasticity" captures the relationship between GDP pc and Flights per person. The regional factor represents all factors that are not covered by the financial aspect of GDP pc. When GDP pc increases by 1-unit Flights per person increase by 1.31 as the elasticity is equal to that number. This formulation was provided by DNV (2023).
Name: GDP_pc[Country] Equation: NAN Unit: USD17ppp/People Documentation: GDP pc is "expressed in 2017 international dollar per person in the country (IMF 2023). It is the purchasing power parity in 2017 International dollars, so it is the amount of 2017 international dollar there is per person. The higher the GDP pc is the richer a country is when accounting for the population. If the GDP pc is lower than each person is poorer and if it increases than the average person in the country is richer. It is measured in 2017 International dollar as to remove inflation from the calculations as that has the potential to hide dynamics. If inflation is high GDP pc will increase because each dollar is worth more but that does not mean that each person is richer as it could mean that they can afford less. Hence, the 2017 International dollars. The data is from 1980 to 2022 and is then extrapolated onward. Despite the Scandinavian countries being advanced economics and thus more prone to S-shaped growth, the GDP pc is extrapolated as it is not the main driver of the model and falls outside the model boundary. Furthermore, the aviation industry increases by around 4% annual this has yet to slow down outside of unprecedented events (such as COVID), thus if the current growth has not slowed than it can be assumed for better or worse that this will continue.
Name: Population[Country] Equation: NAN Unit: People Documentation: This population data was provided by the national statistical databases from the three countries (SSB 2023; SCB 2023; Danmark Statistik 2023). It is the population of three countries between 1980 to 2023 and is then afterwards extrapolated.
Name: Population_Measured_in_Seats[Country] Equation: Population*Seat_Converter Unit: Seats Documentation: The population data is multiplied together with the unit converter to turn the population into airplane seats.
Name: Regional_Adjustment_Factor[Norway] Equation: 1.86 Unit: dmnl Documentation: The regional adjustment factor adjusts the flights per person equation to the reference behaviour. The relationship between GDP pc and Flights per person is not a 100% perfect equation as there are regional differences between each country that can be for various reasons. This factor tries to capture said variations through a number. These numbers were calculated through calibration and linear analysis through excel.

Name: Regional_Adjustment_Factor[Sweden] Equation: 0.9
Name: Regional_Adjustment_Factor[Denmark] Equation: 1.36
Name: Remaining_Share_preferring_Aviation[Country] Equation: (1-Share_of_Population_Willing_to_Travel_via_Alternative_Routes) Unit: dmnl Documentation: As increasing the share of population willing to travel by alternative routes is intended to reduce 'Air Travel Demand', but the converter goes from 0 to 1 it needs to be reversed. By subtracting the share of population willing to travel by alternative routes it gives the intended effect of reducing the demand. If effect variable is equal to 0 then it becomes 1-0 meaning this equation is equal to 0 so the air travel demand is not reduced. If everyone prefers alternative means of transport, then it becomes 1-1 which is equal to 0 meaning the air travel demand is multiplied by 0 so it becomes nothing.
Name: Seat_Converter Equation: 1 Unit: Seats/people Documentation: The data used in the model is measured by seats instead of people and therefore, the population data needs to be converted to airplane seats. Hence, this variable being equal to 1 and having the unit's Seats/people.
Name: Share_of_Population_Willing_to_Travel_via_Alternative_Routes[Norway] Equation: 0.05 Unit: dmnl Documentation: This represents the share of the national population that are willing to travel by trains, car, bike, or bus instead of flying. It is measured from a scale 0 to 1, where 1 means everyone wants to travel by alternative means and 0 is where everyone wants to continue with flying.
Name: Share_of_Population_Willing_to_Travel_via_Alternative_Routes[Sweden] Equation: 0.08
Name: Share_of_Population_Willing_to_Travel_via_Alternative_Routes[Denmark] Equation: 0.25
Fuel Decision Sector:
Name: Cost_of_Fuel_Investment[Country, Fuel] Equation: SMTH1((Cost_of_Constructing_to_meet_Demand), Updating_Perceived_Benefits) Unit: USD Documentation: This represents the delay in receiving the information on costs for a project. Its input is the cost of construction to meet demand and that is also its output, but this is an information delay that takes 4 years to update. It is SMTH1 delay converter since its an information delay. DELAY CONVERTER

Name: Effect_of_CO2_Reductions[Fuel] Equation: GRAPH(((CO2_released_per_Unit_of_Usage[Fuel]//CO2_released_per_Unit_of_Usage[Traditional_Aviation_Fuel]))) Points: (0.000, 1.3000), (0.100, 1.2400), (0.200, 1.1800), (0.300, 1.1200), (0.400, 1.0600), (0.500, 1.0000), (0.600, 0.9400), (0.700, 0.8800), (0.800, 0.8200), (0.900, 0.7600), (1.000, 0.7000) Unit: dmnl Documentation: This effect variables represents the executives view on the CO2 emissions that become reduce per kg of fuel and how that affects the overall fuel attractiveness. The less CO2 a fuel emits the more attractive it is (compared to TAF), thus the higher value the output of this graphical function gives. It compares the CO2 emissions per alternative fuel to the traditional jet fuel. If the CO emissions per kg of fuel is equal to TAF then it is 30% less attractive. If the CO2 emissions are smaller than the TAF emissions, then it becomes attractive to a max of 1.5. This means that if the emissions are lower than TAF it can maximally (assuming a linear relationship) increase attractiveness by 50%.
Name: Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Country, Fuel] Equation: GRAPH(Cost_of_Energy//Cost_of_Energy[Country,Traditional_Aviation_Fuel]) Points: (0.000, 2.000), (0.200, 1.975), (0.400, 1.913), (0.600, 1.767), (0.800, 1.465), (1.000, 1.000), (1.200, 0.5352), (1.400, 0.2331), (1.600, 0.08682), (1.800, 0.02526), (2.000, 0.000) Unit: dmnl Documentation: This effect variables takes the cost of the energy to meet 100% of aviation energy demand. It represents the airport companies viewing the price and seeing if transitioning to the fuel would be expensive to meet the demand. If meeting demand is expensive compared to TAF then it will not be considered as it would cost too much. The graphical function gives an output depending on the value of the input which is comparing the cost of energy of every fuel to the TAF. If the price of the fuel is equal to TAF the input is 1 and the effect variable thus gives a output of 1 meaning it would not change the price as its equal to the current price. If the price goes below the value of TAF then it will increase the attractiveness to a maximum of 2. If the price is larger than TAF cost than it would decrease the value to a maximum of 0 meaning it will not be considered if the cost does not fall within a range around the TAF costs.
Name: Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Country] Equation: GRAPH(Emissions//Target_Emissions) Points: (0.000, 0.9000), (0.200, 0.9025), (0.400, 0.9087), (0.600, 0.9233), (0.800, 0.9535), (1.000, 1.0000), (1.200, 1.0460), (1.400, 1.0770), (1.600, 1.0910), (1.800, 1.0970), (2.000, 1.1000) Unit: dmnl Documentation: This represents the effect that emission targets affect on the fuel attractiveness. It works in the way that if the airports are far off their emission targets the alternative fuels become cheaper since they have less CO2 emission and thus, become more attractive to a certain extent. If the company is far off their target, then the fuel becomes 10% more attractive. If the

emissions are equal to their target, then it becomes equal to 1 and has no effect on the attractiveness. If the emissions somehow are undershot compared to the target the fuels become 10% less attractive as the urgency of switching is less.
Name: Effect_of_Emissions_on_Perceived_Price_of_TAF[Country] Equation: GRAPH(Emissions//Target_Emissions) Points: (0.000, 1), (0.200, 0.9987), (0.400, 0.9957), (0.600, 0.9883), (0.800, 0.9732), (1.000, 0.95), (1.200, 0.9268), (1.400, 0.9117), (1.600, 0.9043), (1.800, 0.9013), (2.000, 0.9) Unit: dmnl Documentation: This represents the fact that if emissions are off their targets the TAF becomes less attractive as the need to transition to alternative fuels becomes greater. If the emissions are equal to the target this effect variable becomes 1 meaning it has no effect on attractiveness. If the emissions are greater than their target than it reduces the attractiveness to a maximum to 90% of its original value.
Name: Effect_of_Supply_on_Fuel_Attractiveness[Country, Fuel] Equation: GRAPH(Comparative_Fuel_Production) Points: (0.000, 0.000), (0.100, 0.06121), (0.200, 0.1289), (0.300, 0.2036), (0.400, 0.2862), (0.500, 0.3775), (0.600, 0.4785), (0.700, 0.590), (0.800, 0.7132), (0.900, 0.8495), (1.000, 1.000) Unit: dmnl Documentation: This effect variable takes the input of supply comparison between SAF production and TAF production. If the SAF production is equal to the TAF production, then the input is equal to 1. If the production of SAF is lower than TAF then the input is below 1. The graphical input gives a corresponding value based on the input. If the value of the input is 0 then the graphical function is 0 as there is not enough supply to be able to meet demand and thus makes the fuel not attractive at all. If the fuel production is equal or larger than TAF production, then the output is equal to 1 meaning the supply has no effect on attractiveness since there is no concern regarding supply chain issues outside of the exogenous events.
Name: Fuel_Attractiveness[Norway, Traditional_Aviation_Fuel] Equation: MAX(0, (Cost_of_Fuel_Investment[Norway,Traditional_Aviation_Fuel]* Effect_of_Supply_on_Fuel_Attractiveness[Norway,Traditional_Aviation_Fuel]) *Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Norway,Traditional_Aviation_Fuel] *Effect_of_Emissions_on_Perceived_Price_of_TAF[Norway]) Unit: USD Documentation: The fuel attractiveness is the scale that measures the attractiveness per fuel. The equation is the cost of fuel investment multiplied by all the effect variables. If the effect variables are lower than 1 then the perceived the benefit becomes lower which results less fuel attractiveness measured in USD. If the cost of construction is high but the effects are low than the fuel attractiveness will decrease.
Name: Fuel_Attractiveness[Norway, Hydrogen] Equation: MAX(0, (Cost_of_Fuel_Investment[Norway,Hydrogen]*Effect_of_Supply_on_Fuel_Attractiveness[Norway,Hydrogen])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Norway,Hydrogen]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Norway])*(Effect_

of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Norway]*Effect_of_CO2_Reductions[Hydrogen]))
Name: Fuel_Attractiveness[Norway, efuels] Equation: MAX(0, (Cost_of_Fuel_Investment[Norway,efuels]*Effect_of_Supply_on_Fuel_Attractiveness[Norway,efuels])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Norway,efuels]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Norway])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Norway]*Effect_of_CO2_Reductions[efuels]))
Name: Fuel_Attractiveness[Norway, Biofuel] Equation: MAX(0, (Cost_of_Fuel_Investment[Norway,Biofuel]*Effect_of_Supply_on_Fuel_Attractiveness[Norway,Biofuel])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Norway,Biofuel]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Norway])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Norway]*Effect_of_CO2_Reductions[Biofuel]))
Name: Fuel_Attractiveness[Sweden, Traditional_Aviation_Fuel] Equation: MAX(0, (Cost_of_Fuel_Investment[Sweden,Traditional_Aviation_Fuel]*Effect_of_Supply_on_Fuel_Attractiveness[Sweden,Traditional_Aviation_Fuel])*Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Sweden,Traditional_Aviation_Fuel]*Effect_of_Emissions_on_Perceived_Price_of_TAF[Sweden])
Name: Fuel_Attractiveness[Sweden, Hydrogen] Equation: MAX(0, (Cost_of_Fuel_Investment[Sweden,Hydrogen]*Effect_of_Supply_on_Fuel_Attractiveness[Sweden,Hydrogen])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Sweden,Hydrogen]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Sweden])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Sweden]*Effect_of_CO2_Reductions[Hydrogen]))
Name: Fuel_Attractiveness[Sweden, efuels] Equation: MAX(0, (Cost_of_Fuel_Investment[Sweden,efuels]*Effect_of_Supply_on_Fuel_Attractiveness[Sweden,efuels])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Sweden,efuels]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Sweden])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Sweden]*Effect_of_CO2_Reductions[efuels]))
Name: Fuel_Attractiveness[Sweden, Biofuel] Equation: MAX(0, (Cost_of_Fuel_Investment[Sweden,Biofuel]*Effect_of_Supply_on_Fuel_Attractiveness[Sweden,Biofuel])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Sweden,Biofuel]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Sweden])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Sweden]*Effect_of_CO2_Reductions[Biofuel]))
Name: Fuel_Attractiveness[Denmark, Traditional_Aviation_Fuel] Equation: MAX(0, (Cost_of_Fuel_Investment[Denmark,Traditional_Aviation_Fuel]*Effect_of_Supply_on_Fuel_Attractiveness[Denmark,Traditional_Aviation_Fuel])*Effect_of_Cost_of_Energy_on_F

uel_Attractiveness[Denmark,Traditional_Aviation_Fuel]*Effect_of_Emissions_on_Perceived_Price_of_TAF[Denmark])
Name: Fuel_Attractiveness[Denmark, Hydrogen] Equation: MAX(0, (Cost_of_Fuel_Investment[Denmark,Hydrogen]*Effect_of_Supply_on_Fuel_Attractiveness[Denmark,Hydrogen])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Denmark,Hydrogen]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Denmark])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Denmark]*Effect_of_CO2_Reductions[Hydrogen]))
Name: Fuel_Attractiveness[Denmark, efuels] Equation: MAX(0, (Cost_of_Fuel_Investment[Denmark,efuels]*Effect_of_Supply_on_Fuel_Attractiveness[Denmark,efuels])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Denmark,efuels]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Denmark])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Denmark]*Effect_of_CO2_Reductions[efuels]))
Name; Fuel_Attractiveness[Denmark, Biofuel] Equation: MAX(0, (Cost_of_Fuel_Investment[Norway,Biofuel]*Effect_of_Supply_on_Fuel_Attractiveness[Norway,Biofuel])*(Effect_of_Cost_of_Energy_on_Fuel_Attractiveness[Norway,Biofuel]*Total_Effect_of_Fuel_Mix_on_Demand_Through_Perceived_Price[Denmark])*(Effect_of_Emissions_on_Perceived_Price_of_Alternative_Fuel[Norway]*Effect_of_CO2_Reductions[Biofuel]))
Name: Share_of_Investment[Country, Fuel] Equation: Fuel_Attractiveness//Total_Fuel_Attractiveness Unit: dmnl Documentation: This divides the fuel attractiveness of each fuel by the total fuel attractiveness. Thus, turning it into a fraction of the total attractiveness. It represents the comparison process of seeing which fuel the airport should invest into.
Name: Target_Emissions[Norway] Equation: IF TIME>2008 AND TIME<2030 THEN HISTORY(Emissions*0.70, 1990) ELSE IF TIME>2030 THEN 0 ELSE Emissions Unit: TonnesCO2/Years Documentation: This represents the climate targets that the government are setting (EP 2021;Royal Norwegian Embassy in Jakarta 2022; UM 2022). The targets chosen are the national targets but taking the aviation industry as a sample of the national we can assume that the target would match the national one as well. The logic statement is to reflect the change in climate targets.
Name: Target_Emissions[Sweden] Equation: IF TIME>2008 AND TIME<2030 THEN HISTORY(Emissions*0.63, 1990) ELSE IF TIME>2030 THEN 0 ELSE Emissions
Name: Target_Emissions[Denmark] Equation: IF TIME>2008 AND TIME<2030 THEN HISTORY(Emissions*0.4, 1990) ELSE IF TIME>2030 THEN 0 ELSE Emissions

Name: Total_Fuel_Attractiveness[Country, Fuel] Equation: SUM(Fuel_Attractiveness[Country,*]) Unit: USD Documentation: This is the total attractiveness of the fuel. It uses the sum function to sum each countries fuel attractiveness measured in USD.
Name: Updating_Perceived_Benefits Equation: 4 Unit: Years Documentation: This is the time it takes for the airport company to adopt their perception of the cost it will take to construct the desired storage.
Infrastructure:
Name: Assest_Lifetime Equation: 35 Unit: Years Documentation: This is the asset lifetime of the storage tanks and infrastructure that the airports use to store all the fuel in. There was little to no data on the subject and therefore, this variable was calibrated and tested.
Name: Completion_of_Hydrogen_Infrastructure[Country] Equation: Hydrogen_Tanks_Under_Construction/Time_to_Complete_Construction Unit: Kilograms/Years Documentation: This flow transfers the under construction stock of hydrogen under construction into the current functional storage stock. It represents the process of completing the construction projects. The equation is stock of under construction over the time it takes to complete the project on average.
Name: Completion_of_TAF_and_Drop_in_Tanks[Country] Equation: TAF_and_Drop_in_Tanks_Under_Construction/Time_to_Complete_Construction Unit: Kilograms/Years Documentation: This flow transfers the under construction stock of TAF and Drop-in under construction into the current functional storage stock. It represents the process of completing the construction projects. The equation is stock of under construction over the time it takes to complete the project on average.
Name: Degradation_of_Storage_Hydrogen[Country] Equation: Hydrogen_Storage_Capacity/Assest_Lifetime Unit: Kilograms/Years Documentation: This is the outflow of the current capacity storage for hydrogen fuels. It is the outflow which means it only drains the current stock of storage capacity. The equation is the stock over the asset lifetime of the storage. This means that as the stock depletes the outflow becomes smaller until it becomes 0 as there is no material left in the storage. This flow cannot deplete the stock past 0.

Name: Degradation_of_Storage_TAF_and_Drop_in[Country] Equation: TAF_and_Drop_in_Storage_Capacity/Assest_Lifetime Unit: Kilograms/Years Documentation: This is the outflow of the current capacity storage for TAF and drop-in fuels. It is the outflow which means it only drains the current stock of storage capacity. The equation is the stock over the asset lifetime of the storage. This means that as the stock depletes the outflow becomes smaller until it becomes 0 as there is no material left in the storage. This flow cannot deplete the stock past 0.
Name: Hydrogen_Storage_Capacity[Country](t) Equation: Hydrogen_Storage_Capacity[Country](t - dt) + (Completion_of_Hydrogen_Infrastructure[Country] - Degradation_of_Storage_Hydrogen[Country]) * dt INIT Hydrogen_Storage_Capacity[Country] = 0 Unit: Kilograms Documentation: This is the stock of storage capacity which represents the storage in kilograms that exist for Hydrogen Fuels. It is initialized to the desired storage since it assumed that in the year 1980 the desired storage is equal to the current storage. It increases through the completion of the storage projects and decreases once the asset has run its lifetime.
Name: Hydrogen_Tanks_Under_Construction[Country](t) Equation: Hydrogen_Tanks_Under_Construction[Country](t - dt) + (Starting_Construction_on_Hydrogen_Tanks[Country] - Completion_of_Hydrogen_Infrastructure[Country]) * dt INIT Hydrogen_Tanks_Under_Construction[Country] = 0 Unit: Kilograms Documentation: This stock represents the extra hydrogen storage units that are currently under construction in each of the three countries. The initial value is 0 since it is assumed that there is no ongoing project in the year 1980. It increases through the flow of starting construction and decreases through completing the construction project. T
Name: New_Drop_in_Storage_Orders[Country] Equation: MAX(0, Storage_needed_for_TAF_and_Drop_in_Fuels-TAF_and_Drop_in_Storage_Capacity) Unit: Kilograms Documentation: This is a goal gap formation that compares the desired storage for TAF and drop-in fuels to the current storage for those types of fuels. If the desired storage is larger than the current, then this converter turns positive which starts the process of constructing more storage. If there is too much storage, then the equation should be negative but due to its maximum function (which always takes the larger number) if it goes negative the variable will be equal to 0.
Name: New_H2_Storage_Orders[Country] Equation: MAX(Desired_Storage[Country,Hydrogen]-Hydrogen_Storage_Capacity, 0)

Unit: Kilograms
Documentation: This is a goal gap formation that takes the desired storage of hydrogen and subtracts the current hydrogen storage capacity from it. So, if the desired storage is larger than current than it will be positive and thus turn, the flow ordering hydrogen tanks to positive which starts the material delay in constructing new hydrogen tanks. If there is too much storage, then the equation should be negative but due to its maximum function (which always takes the larger number) if it goes negative the variable will be equal to 0.

Name: Ordered_Hydrogen_Tanks[Country](t)
Equation: Ordered_Hydrogen_Tanks[Country](t - dt) + (Ordering_Hydrogen_Tanks[Country] - Starting_Construction_on_Hydrogen_Tanks[Country]) * dt

INIT Ordered_Hydrogen_Tanks[Country] = 0

Unit: Kilograms
Documentation: This stock represents the ordered extra storage units for Hydrogen. It increases through the ordering inflow and decreases through the starting constructions flow. Its initial value is 0 since it is assumed that in the year 1980 the infrastructure present matches the desired and thus, there is no need to order more.

Name: Ordered_TAF_and_Drop_in_TAnks[Country](t)
Equation: Ordered_TAF_and_Drop_in_TAnks[Country](t - dt) + (Ordering_TAF_and_Drop_in_TAnks[Country] - Starting_Constructions_on_TAF_amd_Drop_in_Tanks[Country]) * dt

INIT Ordered_TAF_and_Drop_in_TAnks[Country] = 0

Unit: Kilograms
Documentation: This stock represents the ordered extra storage units for TAF and Drop-in fuels. It increases through the ordering inflow and decreases through the starting constructions flow. Its initial value is 0 since it is assumed that in the year 1980 the infrastructure present matches the desired and thus, there is no need to order more.

Name: Ordering_Hydrogen_Tanks[Country]
Equation: New_H2_Storage_Orders/Time_to_Order

Unit: Kilograms/Years
Documentation: This is the flow of ordering hydrogen Storage tanks. It represents the airports ordering new storage as the desired storage is increasing. The equation is the gap between desired and current storage over the time delay it takes to decide to order the storage tanks. It increases the ordered hydrogen tanks.

Name: Ordering_TAF_and_Drop_in_TAnks[Country]
Equation: New_Drop_in_Storage_Orders/Time_to_Order

Unit: Kilograms/Years
Equation: This is the flow of ordering TAF and Drop-in Storage tanks. It represents the airports ordering new storage as the desired storage is increasing. The equation is the gap between desired and current storage over the time delay it takes to decide to order the storage tanks. It increases the ordered TAF and Drop-in tanks.

Name: "Re-Array_Variable"[Norway, Traditional_Aviation_Fuel] Equation: (TAF_and_Drop_in_Storage_Capacity[Norway]*Desired_Share_of_Fuel_Mix[Norway,Traditional_Aviation_Fuel]) Unit: Kilograms Documentation: The purpose of this variable is to reinsert hydrogen into the array since it needed to be separated for the previous structure. It needed to be separate as TAF, e-fuels, and biofuel can use the same infrastructure, but hydrogen cannot.
Name: "Re-Array_Variable"[Norway, Hydrogen] Equation: Hydrogen_Storage_Capacity[Norway]
Name: "Re-Array_Variable"[Norway, efuels] Equation: (TAF_and_Drop_in_Storage_Capacity[Norway]*Desired_Share_of_Fuel_Mix[Norway,efuels])
Name: "Re-Array_Variable"[Norway, Biofuel] Equation: (TAF_and_Drop_in_Storage_Capacity[Norway]*Desired_Share_of_Fuel_Mix[Norway,Biofuel])
Name: "Re-Array_Variable"[Sweden, Traditional_Aviation_Fuel] Equation: (TAF_and_Drop_in_Storage_Capacity[Sweden]*Desired_Share_of_Fuel_Mix[Sweden,Traditional_Aviation_Fuel])
Name: "Re-Array_Variable"[Sweden, Hydrogen] Equation: Hydrogen_Storage_Capacity[Sweden]
Name: "Re-Array_Variable"[Sweden, efuels] Equation: (TAF_and_Drop_in_Storage_Capacity[Sweden]*Desired_Share_of_Fuel_Mix[Sweden,efuels])
Name: "Re-Array_Variable"[Sweden, Biofuel] Equation: (TAF_and_Drop_in_Storage_Capacity[Sweden]*Desired_Share_of_Fuel_Mix[Sweden,Biofuel])
Name: "Re-Array_Variable"[Denmark, Traditional_Aviation_Fuel] Equation: (TAF_and_Drop_in_Storage_Capacity[Denmark]*Desired_Share_of_Fuel_Mix[Denmark,Traditional_Aviation_Fuel])
Name: "Re-Array_Variable"[Denmark, Hydrogen] Equation: Hydrogen_Storage_Capacity[Denmark]
Name: "Re-Array_Variable"[Denmark, efuels] Equation: (TAF_and_Drop_in_Storage_Capacity[Denmark]*Desired_Share_of_Fuel_Mix[Denmark,efuels])
Name: "Re-Array_Variable"[Denmark, Biofuel]

Equation: (TAF_and_Drop_in_Storage_Capacity[Denmark]*Desired_Share_of_Fuel_Mix[Denmark, Biofuel])
Name: Starting_Construction_on_Hydrogen_Tanks[Country] Equation: Ordered_Hydrogen_Tanks/Time_for_Materials_to_arrive Unit: Kilograms/Years Documentation: This flow transfers the kilograms of the ordered hydrogen tanks to the under-construction stock. Its equation is the stock divided by the time it takes for the material to arrive. If the flow is positive, it will decrease the ordered stocks and increase the under-construction stock.
Name: Starting_Constructions_on_TAF_amd_Drop_in_Tanks[Country] Equation: Ordered_TAF_and_Drop_in_TAnks/Time_for_Materials_to_arrive Unit: Kilograms/Years Documentation: This flow transfers the kilograms of the ordered TAF and Drop-in tanks to the under-construction stock. Its equation is the stock divided by the time it takes for the material to arrive. If the flow is positive, it will decrease the ordered stocks and increase the under-construction stock.
Name: TAF_and_Drop_in_Storage_Capacity[Country](t) Equation: TAF_and_Drop_in_Storage_Capacity[Country](t - dt) + (Completion_of_TAF_and_Drop_in_Tanks[Country] - Degradation_of_Storage_TAF_and_Drop_in[Country]) * dt INIT TAF_and_Drop_in_Storage_Capacity[Country] = Storage_needed_for_TAF_and_Drop_in_Fuels Unit: Kilograms Documentation: This is the stock of storage capacity which represents the storage in kilograms that exist for TAF and Drop-in fuels. It is initialized to the desired storage since it assumed that in the year 1980 the desired storage is equal to the current storage. It increases through the completion of the storage projects and decreases once the asset has run its lifetime.
Name: TAF_and_Drop_in_Tanks_Under_Construction[Country](t) Equation: TAF_and_Drop_in_Tanks_Under_Construction[Country](t - dt) + (Starting_Constructions_on_TAF_amd_Drop_in_Tanks[Country] - Completion_of_TAF_and_Drop_in_Tanks[Country]) * dt INIT TAF_and_Drop_in_Tanks_Under_Construction[Country] = 0 Unit: Kilograms Documentation: This stock represents the TAF and Drop-in extra storage units that are currently under construction in each of the three countries. The initial value is 0 since it is assumed that there is no ongoing project in the year 1980. It increases through the flow of starting construction and decreases through completing the construction project.
Name: Time_for_Materials_to_arrive Equation: 4

Unit: Years
Documentation: This is the time it takes for the material that was ordered for the infrastructure projects to arrive. It is set to 5 years assuming there is no delay in the supply chains. 5 years may seem long but due to the specialized nature of the orders it could take a while for it to be custom made and delivered.

Name: Time_to_Complete_Construction
Equation: 6

Unit: Years
Documentation: This is the time it takes to complete any new infrastructure projects. It is set to 6 years to account for the paperwork, deciding where it is supposed to go, if it is supposed to go underground or above ground, and the tediousness in constructing the necessary infrastructure around the storage tanks (delivery aspects).

Name: Time_to_Order
Equation: 3

Unit: Years
Documentation: This is the time it takes for the airports to order new infrastructure material based on their desired level of storage.

Policy:

Name: "POLICY_SWITCH_-_Biofuel_Production_Selection"
Equation: 0

Unit: dmnl
Documentation: This is the policy switch for the biofuel. As biofuel has a large variety of different production and those different supply chains cause different CO2 emissions it was important to switch between them. 1 is the Fischer tropsch method and 2 is the Alcohol to jet.

Reference and Data:

Name: Energy_Used_per_Passenger[Country]
Equation: NAN

Unit: MJ/seats
Documentation: The energy used per passenger is calculated in excel. The Norwegian calculation was provided by DNV (2023). Sweden and Denmark were calculated by duplicating the excel calculations from DNV (2023).

Name: PAXCar[Country]
Equation: NAN

Unit: People
Documentation: This is the total seat capacity from data in all three countries.

Name: PAXdata[Country]
Equation: NAN

Unit: pax Documentation: This variable imports the data for passengers in all three countries. There can be variation as the model only accounts for departures and while the data measures both departures and arrivals.
Name: Ref:_Energy_Demand[Country] Equation: Air_Travel_Demand*Energy_Used_per_Passenger Unit: MJ Documentation: It takes the data of 'Energy per passenger' and multiply it together with the endogenously calculated demand to show a "reference" energy demand.
Name: Total_Fleet_Size[Country] Equation: SUM(Fleet[Country,*]) Unit: Plane Documentation: This sums the fleet per country to find the total number of planes in each fleet at any simulation time. This was mainly used to see how well the model replicated the actual fleet dynamics.
Supply Side:
Name: Actual_Energy_Production[Country] Equation: Maximum_Production_Capacity*Average_Capacity_Factor Unit: kWh Documentation: This takes the maximum potential production in Kwh and multiplies it with the average capacity factor to give the Kwh produced on average. If the average production is 27% then it can be assumed that only 27% of the potential KWh are produced hence, the formulation.
Name: Asset_Degradation[Country] Equation: Production_Assets/Asset_Life_cycle Unit: ProdUnit/Years Documentation: This is the outflow to the stock of production assets. It represents the act of the production assets reaching their lifetime and needing to be replaced. The equation is the stock over the resident time. The resident time is the average asset lifetime of the production units so, on average one production asset leaves the stock every lifetime.
Name: Asset_Life_cycle Equation:22 Unit: Years Documentation: The average asset life cycle is the time on average a wind turbine will be working. After this amount of time, it will need to be replaced. This was taken from EWEA (N/A).
Name: Average_Capacity_Factor Equation: 0.27 Unit: dmnl

Documentation: This is the average capacity factor for the wind turbines in each of the Scandinavian countries. Capacity factor is the fraction of energy produced compared to what the potential production can be. If the winds are not very strong than the capacity factor would be much lower for example. The number was taken from turbines.dk (2023).
Name: Average_Capacity_Factor_for_Fuels[Country, Fuel] Equation: Fuel_Production_Capacity//Percieved_RES_Production_Capacity[Country] Unit: dmnl Documentation: This is the share of the energy production that goes to fuel production capacity. In other words, share of the Kwh that can enter the fuel production factories and be used to fuel production. It is fraction between the Fuel Production Capacity and RES production capacity as it shows the share of the energy grid that goes to the fuel production.
Name: Boost_from_Investment_into_PtX_Plans[Norway, Traditional_Aviation_Fuel] Equation: 1 Unit: dmnl Documentation: P-t-X plans (or P-T-L plans) stands for power to x, which refers to the transformation of (renewable) energy into chemicals and other useful products. The most common plan in Scandinavia is to take offshore wind energy and re-route it into hydrogen production, heating, charging ports, and industry. If there are power to x plans available there is increase in investment into the types of productions. For example, Denmark is highlighting the hydrogen production that will come from their PTX plan (ENS 2021). This variable thus, represents that boost. The countries have different values in each of the fuel since they are prioritizing and investing in different values and different amounts.
Name: Boost_from_Investment_into_PtX_Plans[Norway, Hydrogen] Equation: 1.3
Name: Boost_from_Investment_into_PtX_Plans[Norway, efuels] Equation: 1.15
Name: Boost_from_Investment_into_PtX_Plans[Norway, Biofuel] Equation: 1.1
Name: Boost_from_Investment_into_PtX_Plans[Sweden, Traditional_Aviation_Fuel] Equation: 1
Name: Boost_from_Investment_into_PtX_Plans[Sweden, Hydrogen] Equation: 1.1
Name: Boost_from_Investment_into_PtX_Plans[Sweden, efuels] Equation: 1.15
Name: Boost_from_Investment_into_PtX_Plans[Sweden, Biofuel] Equation: 1.1
Name: Boost_from_Investment_into_PtX_Plans[Denmark, Traditional_Aviation_Fuel] Equation: 1
Name: Boost_from_Investment_into_PtX_Plans[Denmark, Hydrogen] Equation: 1.4
Name: Boost_from_Investment_into_PtX_Plans[Denmark, efuels] Equation: 1.15

Name: Boost_from_Investment_into_PtX_Plans[Denmark, Biofuel] Equation: 1.1
Name: Capacity_Adjustment_time Equation: 4 Unit: Years Documentation: This is the delay in ordering new capacity for fuel production
Name: Capacity_Asset_Lifetime Equation: 5 Unit: Years Documentation: This is the asset lifetime of an electrolysis which is used as the standard unit of the production capacity. After 4.5 years the electrolyser needs to be updated or replaced (Bareiß et al. 2019).
Name: Capacity_Depreciation[Country, Fuel] Equation: Fuel_Production_Capacity/Capacity_Asset_Lifetime Unit: kWh/Years Documentation: This is the outflow to energy that can be used for fuel production. It represents the breaking or degradation of the production units used in the production of SAF. The equation is stock divided by resident time which set to 4.5 years.
Name: CAPEX_per_ProdUnit Equation: 3e6 Unit: USD/Produnit Documentation: This is the cost of purchasing one wind turbine assuming it has a 2-3 MW capacity. The price banana was found on Danish Wind Industry Association (2003).
Name: Change_in_Perception_of_RES_production_capacity[Country] Equation: (Actual_Energy_Production-Percieved_RES_Production_Capacity)/Time_to_Perceive_Changes_in_RES_Production_Capacity Unit: kWh/Year Documentation: This flow is a goal-gap formation that changes the perceived RES production capacity towards the actual energy production. Since it is a goal-gap formation it adjusts the stock towards the actual energy production. If the actual energy production is lower than the flow goes negative to decrease the stock. If the actual energy production is larger than the flow goes positive to increase the stock.
Unit: Change_in_Production_Capacity[Country] Equation: MAX(0, (Desired_Production_Assets_to_meet_RES_Demand-Production_Assets)/Time_to_Update_Production_Capacity) Unit: ProdUnit/Years Documentation: This is the flow that changes the stock of production assets, it takes the desired production assets to meet RES demand and goes into a goal gap formation to increase the stock towards the desired. It has the MAX(0,X) function so that it cannot go

negative as it is unrealistic that companies start to dismantle the wind turbines if they are over producing energy.
Name: Completing_Capacity_Construction[Country, Fuel] Equation: Fuel_Capacity_Ordered/Time_to_Complete_Development Unit: kWh/Years Documentation: This is the flow of capacity ordered to fuel production capacity. It is the stock of ordered capacity over the residency time which is how long it takes to complete a project.
Name: Demand_for_RES[Country] Equation: energy_Demand_in_KWh*Desired_RES_Production Unit: kWh Documentation: This takes the energy demand from the general populace and multiplies it by the share of desired RES production to find how much of that production is desired to be renewable at any simulated time.
Name: Desired_Power_Capacity_for_Fuel_Production[Country, Fuel] Equation: Percieved_RES_Production_Capacity[Country]*Share_of_RES_Production_that_is_consumed_by_the_Fuel_Industry[Country,Fuel]{Percieved_RES_Production_Capacity[Country]*(Percieved_RES_Production_Capacity[Country]//INIT(Percieved_RES_Production_Capacity[Country]))^Elasticity_on_Perceived_RES_Production_on_Capacity_Factor_for_Fuel_Production[Fuel] Unit: kWh Documentation: This takes the Perceived RES Production capacity that the market sees and multiplied it with the share of production that is desires to be used by the fuel industry.
Name: Desired_Production_Assets_to_meet_RES_Demand[Country] Equation: DELAY3(Demand_for_RES//Khw_produced, 5) Unit: ProdUnit Documentation: This calculates the amount of production assets that the energy sector needs to meet the demand for renewable energy. It takes the demand in RES and the amount of energy a production asset can produce in a year (6 million KWh) and delays that over 5 years to represent the delay in the market responding to demand. It is assumed that a production asset is a wind turbine as that is the focus of the energy transition currently. It could also be hydro power and geothermal power but except for Norway wind turbine are currently dominating the market. DELAY CONVERTER
Name: Desired_RES_Production[Country] Equation: NAN Unit: dmnl Documentation: The desired RES production is the amount of the energy power production that policymakers want to consist of renewable energy. The data used is a proxy for the actual variable. The data is the percentage of energy consumption that is from renewable sources and only goes to until 2019 (The World Bank 2019; Nordic Energy Research 2015;

IRENA 2020; IRENA 2019). To extrapolate the the year that each country thinks they will reach 100% is put into the excel file and the data is then extrapolated until that year (The World Bank 2019; Nordic Energy Research 2015; IRENA 2020; IRENA 2019).

Name: Economics_of_Scale_RES[Country]
Equation: GRAPH(Production_Assets//"EOS_-_RES") Points: (0.000, 1.750), (0.200, 1.600), (0.400, 1.450), (0.600, 1.300), (0.800, 1.150), (1.000, 1.000), (1.200, 0.850), (1.400, 0.700), (1.600, 0.550), (1.800, 0.400), (2.000, 0.250)

Unit: dmnl
Documentation: This graphical function takes the amount of production assets and divides it by the EOS-RES which stands for economies of scale for renewable energy. It is meant to represent that as one gets more of a certain production asset it becomes easier and cheaper to collect more due to economies of scale.

If the production asset is equal to EOS-RES then the graphical function gives it the value of 1 meaning the function has no effect on future equations. If there are less production assets than the EOS the graphical function increases the costs linearly to a maximum of 1.75. This means that the price will be 75% more expensive as it is expensive to produce. If there are more production assets than the EOS-RES then the effect will decrease the price to maximum of 0.25. This means that the effect variable will reduce price to 25% of the original/normal price.

Name: Effect_of_Fuel_Availability_on_LCOE_per_Fuel[Country, Fuel]
Equation: GRAPH(Fuel_able_to_be_produced//Reference_Production_TAF[Country]) Points: (0.000, 1.800), (0.200, 1.780), (0.400, 1.731), (0.600, 1.614), (0.800, 1.372), (1.000, 1.000), (1.200, 0.6282), (1.400, 0.3864), (1.600, 0.2695), (1.800, 0.2202), (2.000, 0.200)

Unit: dmnl
Documentation: This graphical function compares the amount of SAF that can be produced to the production of Jet A1 in each of the three countries. It is assumed that that there is no export or importing so that each country only uses the fuel that can produce individually. It takes the fuel that can be produced and compare it (divide it by) the reference Jet A1 production (measured in barrel converted to kg annually).

If the fuel able to be produce is equal to the Jet A1 production, then the graphical function is equal to 1 meaning there is no effect on price. If the fuel able to be produced is lower than the jet A1 production, then the effect will increase the price to maximum of 1.8. If the fuel able to be produced is larger than the jet A1 production, then the effect will decrease towards a maximum of 0.2. Resulting in a 20% price compared to the normal.

Name: Effect_of_Fuel_Demand_on_Fuel_Production_Capacity[Country, Fuel]
Equation: GRAPH(Actual_Share_of_Fuel_Mix) Points: (0.000, 0.9000), (0.100, 0.9122), (0.200, 0.9258), (0.300, 0.9407), (0.400, 0.9572), (0.500, 0.9755), (0.600, 0.9957), (0.700, 1.0180), (0.800, 1.0430), (0.900, 1.0700), (1.000, 1.1000)

Unit: dmnl
Documentation: This effect variable represents the act that demand can have on production. If there is a lot of demand for a specific fuel, then the supply side will want to produce more and increase production so that they can increase profits. The input is the actual share of fuel mix which can increase from 0 to 1 and all number between. If the share of the fuel mix

is equal to 1 then the graphical function increases to a max of 1.1 which results in a 10% increase in production. IF the actual share of fuel mix decreases towards 0 it will decrease the desired production to a lowest of 0.9.
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Norway, Traditional_Aviation_Fuel] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000) Unit: dmnl Documentation: This graphical function is the effect that the adoption of hydrogen planes has on the production of hydrogen. Hence, the other graphical functions being always equal to 1 (no effect). If there are no hydrogen planes in the fleet than the effect will decrease the share of hydrogen production by 0.9. If half of the fleet is hydrogen than the effect will be 1 meaning, there is no decrease to hydrogen production. If 100% of the fleet is hydrogen than it will increase the hydrogen production by 10% (1.1). It is meant to represent the market seeing that hydrogen is becoming more popular and thus, reacts to that information by wanting to produce more.
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Norway, Hydrogen] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (0.000, 0.9000), (0.100, 0.9025), (0.200, 0.9087), (0.300, 0.9233), (0.400, 0.9535), (0.500, 1.0000), (0.600, 1.0460), (0.700, 1.0770), (0.800, 1.0910), (0.900, 1.0970), (1.000, 1.1000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Norway, efuels] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Norway, Biofuel] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Sweden, Traditional_Aviation_Fuel] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Sweden, Hydrogen] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (0.000, 0.9000), (0.100, 0.9025), (0.200, 0.9087), (0.300, 0.9233), (0.400, 0.9535), (0.500, 1.0000), (0.600, 1.0460), (0.700, 1.0770), (0.800, 1.0910), (0.900, 1.0970), (1.000, 1.1000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Sweden, efuels] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Sweden, Biofuel]

Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Denmark, Traditional_Aviation_Fuel] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Denmark, Hydrogen] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (0.000, 0.9000), (0.100, 0.9025), (0.200, 0.9087), (0.300, 0.9233), (0.400, 0.9535), (0.500, 1.0000), (0.600, 1.0460), (0.700, 1.0770), (0.800, 1.0910), (0.900, 1.0970), (1.000, 1.1000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Denmark, efuels] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen[Denmark, Biofuel] Equation: GRAPH(Share_of_Fleet_being_Hydrogen_Planes[Country]) Points: (1.000, 1.000), (1.100, 1.000), (1.200, 1.000), (1.300, 1.000), (1.400, 1.000), (1.500, 1.000), (1.600, 1.000), (1.700, 1.000), (1.800, 1.000), (1.900, 1.000), (2.000, 1.000)
Name: Effect_of_Price_of_Fuel_on_Production[Country, Fuel] Equation: GRAPH(Price_per_Fuel//Price_per_Fuel[Country,Traditional_Aviation_Fuel]) Points: (0.000, 1.2000), (0.200, 1.1780), (0.400, 1.1500), (0.600, 1.1150), (0.800, 1.0700), (1.000, 1.0000), (1.200, 0.9405), (1.400, 0.8491), (1.600, 0.7331), (1.800, 0.5862), (2.000, 0.4000) Unit: dmnl Documentation: This is the effect of price on fuel production. It represents the if any fuel becomes cheaper than the price of the traditional aviation fuel then the production side has more incentive to produce more sustainable aviation fuel. If the fuel is equal to the traditional jet fuel, then the effect variable is equal to 1 meaning there is no effect. If the price of the SAF is higher than the TAF then the effect will decrease the incentives to produce more to a maximum of 0.4. If the price becomes lower than the TAF price, then it can increase the production by a max of 1.2 or 20% more than normal.
Name: Effect_of_Production_on_CAPEX_&_OPEX_of_Fuel_Production[Country, Fuel] Equation: GRAPH((Fuel_Production_Capacity/"EOS_-_Fuel_Production")) Points: (0.000, 1.900), (0.200, 1.877), (0.400, 1.822), (0.600, 1.690), (0.800, 1.418), (1.000, 1.000), (1.200, 0.5817), (1.400, 0.3097), (1.600, 0.1781), (1.800, 0.1227), (2.000, 0.100) Unit: dmnl Documentation: This graphical function represents the fuel production capacity towards the threshold of the economies of scale on fuel production. The actual fuel production is compared to the threshold and does not increase past 1 until the EOS threshold is reached. If the fuel production capacity is equal to the EOS - Threshold, then the graphical functions output is 1 meaning it has no effect. If the fuel production is lower than the EOS threshold, then the effect will increase the costs to a maximum effect of 1.9 meaning it will be 90%

more expensive. If the Fuel production capacity is larger than the EOS threshold the effect decreases to the maximum of the 0.1 which means the price will be reduced to maximum of 10% of the original price.
Name: Energy_Demand_in_KWh[Country] Equation: (Population*Energy_use_PC)*GJ_into_KWh Unit: kWh Documentation: This takes the energy use per capita, population, and GJ into Kwh conversion to find the amount of energy that population use in Kwh as a proxy for energy demand in the country. This will then be used to drive the supply of energy production in the system. The reason that this is used a proxy instead of using energy production data is 1) the data is easy to find but does not cover all the years and 2) it does not include export/imports etc. Therefore, it was easier to have demand drive supply as a proxy.
Name: Energy_use_PC Equation: NAN Unit: GJ/People Documentation: This is the energy use per capita in total, so it encompasses every facet of life per person in the Nordic countries, so it is not country specific. The data was collected and made presentable by Nordic Energy Research (2020), a subsidiary of the Nordic Council. Due to it being the Nordic usage there is a lack of variation in the three Scandinavian countries but since this is not the focus of the model, it is an acceptable proxy.
Name: "EOS_-_Fuel_Production" Equation: 20e9 Unit: Kwh Documentation: This is economies of scale for fuel production. It is the threshold before the economies of scale effects kick in. It is set to 20e9 from calibration and sensitivity testing.
Name: "EOS_-_RES" Equation: 3000 Unit: ProdUnit Documentation: This is the economies of scale for renewable energy production. It is set to 3000 due to calibration and sensitivity testing.
Name: Fuel_able_to_be_produced[Country, Fuel] Equation: Production_for_Fuel//Khw_needed_to_produce_Fuel Unit: Kilograms Documentation: By dividing the production of fuel by KWh needed to produce fuel finds the actual fuel in kilograms the systems can produce.
Name: Fuel_Capacity_Ordered[Country, Fuel](t) Equation: Fuel_Capacity_Ordered[Country, Fuel](t - dt) + (Ordering_New_Capacity[Country, Fuel] - Completing_Capacity_Construction[Country, Fuel]) * dt INIT Fuel_Capacity_Ordered[Country, Fuel] = 0

Unit: kWh Documentation: This stock represents any planned projects to increase fuel production capacity. That can be through electrolysers or any measure to increase the production of it measured in KWh. It increases through ordering new capacity inflow and decreases through the completing capacity construction. The time it takes for the fuel capacity ordered to be completed represents the time it takes to finish the fuel production plants.
Name: Fuel_Production_Capacity[Country, Fuel](t) Equation: Fuel_Production_Capacity[Country, Fuel](t - dt) + (Completing_Capacity_Construction[Country, Fuel] - Capacity_Depreciation[Country, Fuel]) * dt INIT Fuel_Production_Capacity[Country, Fuel] = 0 Unit: kWh Documentation: This is the fuel production capacity measured in KWh. It is energy that can be used to make the SAFs. It increases through the flow of completing capacity construction and remains in the stock for 4.5 years before either needing to be replaced or repaired. The initial value is 0 as even if there is production of the e-fuels etc in the 1980, it will not be made with renewable energy and therefore, is not relevant for the model. Since if it is not made with renewable techniques, it simply making a different fuel that still emits CO2.
Name: GJ_into_KWh Equation: 277.778 Unit: KWh/GJ Documentation: This is the conversion factor from Gigajoule into Kilowatt-hours.
Name: GW[Country, Fuel] Equation: Production_for_Fuel/Kwh_to_GWh Unit: Gwh Documentation: This measures the fuel production lines capacity in GWH instead of Kilowatt-hours.
Name: Indicated_Capacity[Country, Fuel] Equation: MAX(0, Desired_Power_Capacity_for_Fuel_Production-Fuel_Production_Capacity) Unit: KWh Documentation: This is a goal gap formation that takes the stock of the production capacity and subtracts it from the desired capacity. This variable is then used in the flow to show the missing capacity that needs to be added to meet the desired capacity. If the desired is equal to the actual capacity, then this converter is 0 which means the inflow to the fuel capacity ordered is also 0 since there is no need to increase the capacity as they have all they already want.
Name: Khw_needed_to_produce_Fuel[Norway, Traditional_Aviation_Fuel] Equation: 0 Unit: KWh/Kg Documentation: This variable is the amount of energy it takes to produce the 1 kg of the specific fuel. All the sustainable aviation fuels take different amount of energy to produce

depending on the energy intensity of the process. TAF is set to 0 since we are not interested in how much of regular jet fuel can be produced. This number is actually a calculation that every machine needs to do and cannot be pinned to a specific value as there is a varying range of needed variables such as heat, water, how much molecules, what type of energy is feeding the machine, and the type of energy transformation. However, the following sources stated based on their complex calculations the number used here (FCHJU 2014;Hillestad et al. 2018; Trinh 2021; Hao et al. 2021).
Name: Khw_needed_to_produce_Fuel[Norway, Hydrogen] Equation: 53
Name: Khw_needed_to_produce_Fuel[Norway, efuels] Equation: 10
Name: Khw_needed_to_produce_Fuel[Norway, Biofuel] Equation: 15.16
Name: Khw_needed_to_produce_Fuel[Sweden, Traditional_Aviation_Fuel] Equation: 0
Name: Khw_needed_to_produce_Fuel[Sweden, Hydrogen] Equation: 53
Name: Khw_needed_to_produce_Fuel[Sweden, efuels] Equation: 10
Name: Khw_needed_to_produce_Fuel[Sweden, Biofuel] Equation: 15.16
Name: Khw_needed_to_produce_Fuel[Denmark, Traditional_Aviation_Fuel] Equation: 0
Name: Khw_needed_to_produce_Fuel[Denmark, Hydrogen] Equation: 53
Name: Khw_needed_to_produce_Fuel[Denmark, efuels] Equation: 10
Name: Khw_needed_to_produce_Fuel[Denmark, Biofuel] Equation: 15.16
Name: Khw_produced[Country] Equation: 6e6 Unit: Kwh/ProdUnit Documentation: This is average annual energy production per wind turbine (EWEA N/A).
Name: Kwh_to_GWh Equation: 1e6 Unit: Kwh/Gwh Documentation: This is the conversion factor from Kwh to Gwh.
Name: LCOE[Country] Equation: (Production_Assets*(CAPEX_per_ProdUnit+OPEX_per_ProdUnit*Economics_of_Scale_RES))//(Khw_produced*Production_Assets)

Unit: USD/Kwh Documentation: LCOE stands for levelized cost of electricity. LCOE is the price of the electricity generated accounting for total electricity generation. The formula is sum of the lifetime costs divided by the sum of the electricity energy produced over a lifetime. So costs expressed over the power generated. The equation here then takes the costs multiplied with the stock to find the total costs divided over the energy produced per production asset.
Name: Maximum_Production_Capacity[Country] Equation: (Khw_produced*Production_Assets) Unit: kWh Documentation: A wind turbine can produce 6 million KWh hour annually if it is operating at maximum capacity which this variable assumes. Multiplying the KWh with the stock of production assets gives the total energy output if each wind turbine was operating at maximum capacity.
Name: Normal_Share_of_Fuel_Energy_Consumption[Traditional_Aviation_Fuel] Equation: 0 Unit: dmnl Documentation: The normal share of investment represents the desired share of the energy produced to go to that specific field. There was no data on this matter and thus, the variables are sensitivity tested and calibrated
Name: Normal_Share_of_Fuel_Energy_Consumption[Hydrogen] Equation: 0.08
Name: Normal_Share_of_Fuel_Energy_Consumption[efuels] Equation: 0.06
Name: Normal_Share_of_Fuel_Energy_Consumption[Biofuel] Equation: 0.1
Name: OPEX_and_CAPEX_of_Fuel_Production[Country, Fuel] Equation: (LCOE[Country]*Khw_needed_to_produce_Fuel)*Effect_of_Production_on_CAPEX_&_OPEX_of_Fuel_Production Unit: USD/Kg Documentation: The CAPEX and OPEX costs were taken from Department for Business, Energy & Industrial Strategy (2021).
Name: OPEX_per_ProdUnit Equation: 35000*22 Unit: USD/ProdUnit Documentation: This is the operational costs of maintaining a wind turbine for the whole lifetime of the wind turbine. It takes the operational cost per year and multiplies it with the lifetime to find lifetime cost. The costs were found from Christensen (2022).
Name: Ordering_New_Capacity[Country, Fuel] Equation: (Indicated_Capacity/Capacity_Adjustment_time)

Unit: kWh/Years Documentation: This is the flow of ordering new capacity for fuel production. It represents the companies that produce fuel slowly trying to increase their current capacity towards their desired or indicated capacity. It
Name: Percieved_RES_Production_Capacity[Country](t) Equation: Percieved_RES_Production_Capacity[Country](t - dt) + (Change_in_Perception_of_RES_production_capacity[Country]) * dt INIT Percieved_RES_Production_Capacity[Country] = Actual_Energy_Production Unit: kWh Documentation: This information stock is the perceived RES Production capacity, meaning it is the market perception of the energy production from renewable sources. It is perceived because the actors within the market may be slow to realize that the energy production has increased and can therefore, invest into sustainable alternative that are made using green energy.
Name: PRICE[Country, Fuel] Equation: OPEX_and_CAPEX_of_Fuel_Production*Effect_of_Fuel_Availability_on_LCOE_per_Fuel*Effect_of_Demand_on_Price Unit: USD/Kilogram Documentation: This is the price of the fuel after the effect of supply, demand, and production costs are accounted for. It multiplies the opex and capex costs with the effects of demand (which increases) and supply (which decreases) the price. This is to represent the effect that the price curve would have on the fuel. CAPEX and OPEX would most likely not be effect by supply and demand and then determine price. However, this method is a simplified price structure and therefore affecting the supply side costs is meant to represent the fact that the more demand is on there the cheaper it would be to produce due to various reasons. Hence, instead of the normal price and having effects increase/decrease it this represents the whole process of price affects.
Name: Production_Assets[Country](t) Equatiobn: Production_Assets[Country](t - dt) + (Change_in_Production_Capacity[Country] - Asset_Degradation[Country]) * dt INIT Production_Assets[Country] = Desired_Production_Assets_to_meet_RES_Demand Unit: ProdUnit Documentation: This stock contains all RES production assets in each country. It increases through the flow of change in production capacity and decreases through the asset degradation flow. The initial value is set to the desired as it would then match how it is at start time so there is not a large jump at time 0.
Name: Production_for_Fuel[Country, Fuel] Equation: DELAY3(Actual_Energy_Production[Country]*Average_Capacity_Factor_for_Fuels[Country,Fuel], Time_to_Produce) Unit: kWh

Documentation: This delay converter represents the actual production of the fuel. It takes the average capacity and multiplies it with the actual energy production to show how much of the energy production is dedicated to fuel production. DELAY CONVERTER
Name: Reference_Production_TAF[Norway] Equation: (11790*1000)*365 Unit: Kilograms Documentation: This is the amount of Jet fuel produced in each country. The data includes any kerosene or naphtha type fuels. The data was taken from the Global Economy (2023a; 2023b; 2023c) and was originally measured in barrels per day. Since it was measured in barrels, we convert to kg by multiplying it by 1000 since there is 1000 kg in a barrel. This is followed by multiplying it with 365 to find the average annual production of barrels.
Name: Reference_Production_TAF[Sweden] Equation: (5000*1000)*365
Name: Reference_Production_TAF[Denmark] Equation: (2960*1000)*365
Name: Share_of_RES_Production_that_is_consumed_by_the_Fuel_Industry[Country, Fuel] Equation: Normal_Share_of_Fuel_Energy_Consumption[Fuel]*Effect_of_Price_of_Fuel_on_Production*Effect_of_Fuel_Demand_on_Fuel_Production_Capacity*Effect_of_Hydrogen_Fleet_on_Production_of_Hydrogen*Boost_from_Investment_into_PtX_Plans Unit: dmnl Documentation: This is the share of energy produced that the industry wants to be available to sustainable aviation fuel. It takes the normal share of the energy consumption and multiply it with the effect of price, demand, PtX plans, and specifically on hydrogen there is also the effect of the fleet. This means there are various reasons that the production can increase or decrease.
Name: TAF_Price Equation: NAN Unit: USD/Kilogram Documentation: This is the price of traditional kerosene jet fuel data between the year 1990 to 2020. After the year 2020, it takes the constant price sine extrapolating due to the trend line would cause a rapid decline or incline. The data was taken from (EIA 2022).
Name: Time_to_Complete_Development Equation: 7 Unit: Years Documentation: This is time it takes to complete the fuel capacity projects, so once the delay is done they are fully operational.
Name: Time_to_Perceive_Changes_in_RES_Production_Capacity Equation: 5

Unit: Years Documentation: This is the time it takes for the perception of the fuel companies to see what the energy sector can produce greenly.
Name: Time_to_Produce Equation: 1 Unit: Years Documentation: This is the time it takes to actually produce the fuels. It is set to 1 year.
Equation: Time_to_Update_Production_Capacity Equation: 8 Unit: Year Documentation: This is the time it takes to construct the renewable energy production assets. It is set to 8 years as that is the length it takes to complete a wind turbine farm.

Array Dimension	Indexed by	Elements
Country	Label (3)	Norway Sweden Denmark
Flights	Label (3)	Short_Haul Medium_Haul Long_Haul
Fuel	Label (4)	Traditional_Aviation_Fuel Hydrogen efuels Biofuel