Master's Thesis – master Energy Science

Including the emissions from international bunker fuels in greenhouse gas targets

A techno-economic analysis of the implications for the Dutch energy system in 2030 and 2050

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Abstract

The 1997 decision by the UNFCCC to exclude the greenhouse gas (GHG) emissions from international bunker fuels (IBFs) from the Kyoto protocol has left a large portion of the global GHG emissions unaccounted for. Addressing these emissions is necessary if serious efforts are to be made to limit global temperature rise in line with the Paris agreement. However, difficulties related to the allocation of these emissions have previously prevented action from being undertaken.

In this study, Dutch statistics regarding the flow of freight and persons are used to calculate a demand for marine and jet fuels that is placed under the responsibility of the Netherlands. Next, forecasts from literature are used to project how high this demand will be in 2030 and 2050. Results from this part of the study project that the Netherlands will be responsible for a demand of 178 PJ marine fuels and 166 PJ jet fuels in 2030. In 2050, the Netherlands is projected to be responsible for a demand of 155 PJ marine fuels and 208 PJ jet fuels.

During the second part of this study it is investigated how the Netherlands can best meet its future energy needs if the emissions from the IBFs it is held accountable for are included in the countries GHG reduction targets. This part of the research is carried out with the aid of the national energy model OPERA.

The results show that a high energy demand and low supply of renewable energy resources in the Netherlands make it challenging for the country to achieve its national GHG reduction targets, even if the emissions from IBFs are excluded in these targets. If the emissions from IBFs are included in the Dutch GHG reduction targets, compliance with these targets while meeting all national energy needs becomes much more expensive as competition over limited renewable resources increases. In many scenarios, compliance with the GHG reduction targets is only possible if large amounts of biomass can be imported and if the potential of carbon capture and storage (CCS) is sufficiently high.

Preface

This research was written as a part of the graduation requirements of the two-year master Energy Science at Utrecht University, the Netherlands. Developed by the Copernicus Institute of Sustainable Development this master's programme focusses on the analysis of energy systems and their transition towards a sustainable future.

ECN part of TNO was the host organization during the project, whom I am grateful for giving me an inspiring place to work and allowing me to use their energy model OPERA. A word of thanks also to my supervisors Joost and Ric. Thank you Joost for introducing me to the world of energy modelling and for your willingness to answer my many questions regarding OPERA and this thesis in general. I have gotten to know you as a very kind-hearted person who always made time to help out others. Thank you Ric for not only providing me with useful feedback but also for motivating me during the project. I found your enthusiasm about the subject very contagious and enjoyed the occasional anecdote about the time you had to write your own master's thesis.

List of abbreviations

AtJ	alcohol-to-jet
CCS	carbon capture and storage
DME	dimethyl ether
GCD	great circle distance
GHG	greenhouse gas
HEFA	hydroprocessed esters and fatty acids
HFO	heavy fuel oil
HTL	hydrothermal liquefaction
IATA	International Air Transport Association
IBF	international bunker fuel
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
RPK	revenue passenger kilometre: a measures of passenger traffic including both the amount of passengers and distance travelled. Excludes non-paying passengers such as flight attendants.
RTK	revenue tonne kilometre: a measure of freight traffic including both the mass and distance travelled. The mass of infrastructure (e.g. the mass of the container or aircraft) is not included.
S-AIS	satellite automatic identification system
SNG	substitute natural gas
UCO	used cooking oil
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction

1.1. Background of this thesis

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) expressed its objective of achieving the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*" (United Nations, 1992). This objective was later quantified under the Kyoto Protocol in which endorsing parties committed themselves to country-specific reduction targets for greenhouse gas (GHG) emissions (United Nations, 1997). However, the GHG emissions from international bunker fuels[1] (IBFs) were explicitly excluded from these targets (Oberthür, 2003; Yamin & Depledge, 2004). Instead the decision was made that emissions from IBFs would be reported separately from the national total while their reduction would be pursued through two existing UN agencies: the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) (United Nations, 1997; Yamin & Depledge, 2004). This decision was left unchanged in the 2016 follow-up of the Kyoto protocol - the Paris agreement - in which endorsing parties agreed to limit the global temperature rise to well below 2° C in reference to pre-industrial levels (UNFCCC, 2015; UNFCCC, 2018).

In the years following the Kyoto Protocol the IMO & ICAO made little progress towards implementing meaningful and concrete regulation for the reduction of GHG emissions from IBFs (Cames et al., 2015; Romera, 2016). Among the several reasons for this are the conflicting interests within these two organizations, the importance of equal treatment by all countries in the internationally competitive shipping and aviation sectors and the fact that ship and aircraft registrations can easily be changed to the country in which legislation is most beneficial (Romera, 2016). In fact, a concrete GHG reduction target for the aviation sector was first proposed not by the ICAO but by the International Air Transport Association (IATA), a trade organization representing airlines responsible for some 93% of scheduled international air traffic. In 2009 the IATA suggested that the sector should strive to stabilize its CO_2 emissions by 2020 and achieve a 50% reduction of CO_2 emissions by 2050 in reference to 2005 (IATA, 2009). The regulatory framework later adopted by the ICAO was far less ambitious and only stated that CO_2 emissions from international aviation should stabilize from 2020 onwards, without mentioning a future target for further reduction (ICAO, 2013). Additionally noteworthy is that carbon offsetting was included as an option to reach the objective (ICAO, 2016a). A GHG reduction target for international shipping was only recently agreed upon. In March 2018 the IMO announced its ambition to "*peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out (…) on a pathway of* CO_2 *emissions reduction consistent with the Paris Agreement temperature goals.*" (IMO, 2018).

The necessity of successful regulation of GHG emissions from international shipping and aviation to achieve the goals of the Paris Agreement was also underlined in a study by Cames et al. (2015). The authors found that if current regulation within the shipping and aviation sectors remained unchanged, their combined shares of the global CO_2 emissions could rise substantially from 4.2% in 2012 to 40% in 2050. Contrastingly the sectors would have to reduce their combined GHG emissions in 2050 by at least 55% in reference to 2005 in order to make a serious contribution to a maximum global temperature rise of 2° C. The authors conclude that technological and operational improvements are

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[1] In this report international bunker fuels refer to the fuels used for international transport (of both passengers and freight) by the shipping and aviation sectors.

insufficient for reaching this target and that a combination of measures including demand reduction, fuel substitution and carbon offsetting are required.

The conclusions of Cames et al. (2015) are especially valid for the Netherlands. In 2015, IBF sales in the Netherlands amounted to 515 PJ for international shipping and 158 PJ for international aviation, respectively 6.0% and 2.1% of global sales (IEA, 2018). At the same time the Netherlands committed itself to ambitious GHG reduction targets to comply with the Paris agreement. In reference to 1990, Dutch GHG emissions should be reduced by 49% in 2030 and 95% in 2050 (Rijksoverheid, 2018). Figure 1 compares the GHG emissions from IBFs sold in the Netherlands to the (intended) national GHG emissions. It shows that while the national GHG emissions are in decline and are required to continue declining, the GHG emissions from IBFs are projected to increase. As a result, GHG emissions from IBFs sold in the Netherlands could be half as much as all other Dutch emissions by 2030. If the trend projected towards 2030 continues, GHG emissions from IBFs sold in the Netherlands could even surpass the national emissions before 2050.

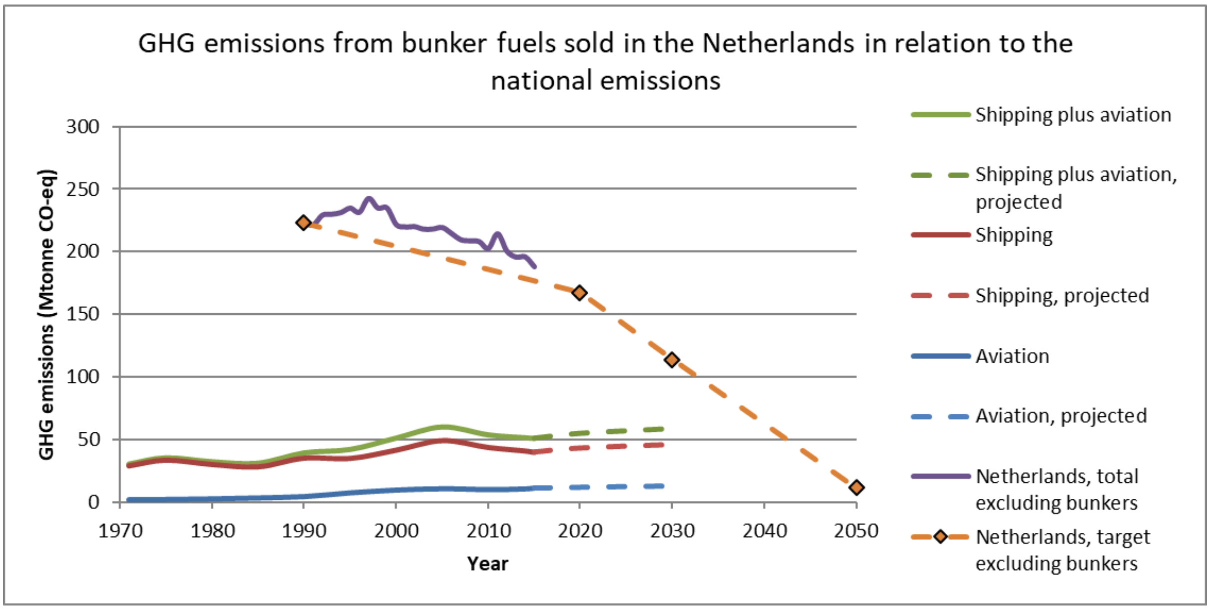

Figure 1: past and projected GHG emissions from IBFs sold in the Netherlands compared to all other Dutch GHG emissions. Sources: IEA (2017) for past emissions from IBFs sold in the Netherlands; PBL (2017) for past national GHG emissions; Geilenkirchen et al. (2016) for projected GHG emissions from IBFs sold in the Netherlands. The Dutch GHG reduction targets in reference to 1990 are 25% in 2020, 49% in 2030 and 95% in 2050 (Rijksoverheid, 2018).

1.2. Research objectives

The increasing global share of GHG emissions from IBFs and the recent policy announced by the IMO and ICAO require that significant efforts are made to reduce GHG emissions from international shipping and aviation. The implications of such efforts could be noticeable not only within the international shipping and aviation sector but also outside of these sectors (Ros & Daniëls, 2017). De Jong et al. (2017) previously studied the implications of efforts to reduce GHG emissions from international shipping and aviation at a European level. However, a specific study for the Netherlands is currently lacking. The objective of this research is therefore to determine how varying efforts to reduce GHG emissions from international shipping and aviation would impact the layout of the future Dutch energy system. This is done while taking the complex interlinkages within the Dutch energy system into account with sectors that often compete for the same resources. Given that the GHG emissions from international shipping and aviation revolve mainly around the production and consumption of marine and jet fuels, the main research objective is phrased as follows:

How does accounting for the GHG emissions from international bunker fuels change the most cost-effective way in which the Dutch GHG emission reduction targets of 2030 and 2050 can be achieved?

To answer the main research question it should first be determined what the future demand for IBFs in the Netherlands will be. This includes choosing an *allocation approach* that determines the amount IBF demand the Netherlands can fairly be held accountable for. This is covered in the first sub-question:

1. *What is the projected demand for IBFs in 2030 and 2050 that can be allocated to the Netherlands?*

Next it needs to be determined which options are available to meet the future Dutch demand for IBFs. These consist of fossil and renewable pathways by which marine and jet fuels can be produced. To determine the competitiveness of each of these production pathways information about the future performance with respect to costs, resource consumption and GHG emissions is required. This is the subject of the second sub-question:

2. *What are the projected costs, resource consumption and GHG emissions of marine and jet fuel production pathways available in 2030 and 2050?*

Accounting for the GHG emissions from IBFs can be done in multiple ways representing different policy scenarios. Two of such policy scenarios and one reference scenario are investigated in this study. In each case the outcome of a scenario is compared to the reference scenario in which the GHG emissions from IBFs are not accounted for. The third sub-question of this research focusses on the reference scenario:

3. *How can the Dutch GHG emission reduction targets of 2030 and 2050 be most effectively achieved if the GHG emissions from IBFs are not accounted for?*

In the first policy scenario, IBF emissions remain excluded from the national emissions but the IMO and ICAO implement sector-specific GHG reduction targets that the Netherlands has to comply with. These targets are set in accordance with the current IMO & ICAO ambitions. This scenario is expressed in the fourth sub-question:

4. *How can the Dutch GHG emission reduction targets of 2030 and 2050 be most effectively achieved if the Netherlands implemented the sector-specific GHG emission reduction targets proposed by the IMO & ICAO?*

While it seems likely that future regulation of GHG emissions from IBFs will continue to be implemented through the IMO & ICAO one could argue that a sector-specific reduction target could have undesirable effects. First, the targets set by the IMO & ICAO remain far less ambitious than those for the other sectors of the Dutch economy. It is therefore questionable whether the overall GHG reduction that would be achieved in 2030 and 2050 is compatible with the goals of the Paris Agreement. Second, in order to minimize the overall costs of GHG reduction, any additional GHG reduction should be acquired in the sector where the marginal GHG reduction costs are the lowest. Sector-specific GHG reduction targets could therefore unnecessarily increase the overall costs of the energy system (Heitmann & Khalilian, 2011). This occurs when the marginal costs of GHG mitigation in the international shipping and aviation sectors are either higher or lower than those in the other sectors, for example road transport or electricity generation. Sub-question five will therefore investigate a Policy scenario in which the Netherlands maintains its overall GHG reduction targets of 49% in 2030 and 95% in 2050 (in line with the objectives of the Paris Agreement) while including the GHG emissions from IBFs in this overall target:

5. *How can the Dutch GHG emission reduction targets of 2030 and 2050 be most effectively achieved if the GHG emissions from IBFs are added to the total Dutch emissions while the overall national GHG reduction targets remain unchanged?*

1.3. Outline

Chapter 2 of this report describes the methodology that was used to carry out this study. The first part of the results, the projected demand for marine and jet fuels that is allocated to the Netherlands, is shown in chapter 3 and 4 alongside a description of their calculation process. The projected costs, resource consumption and GHG emissions of marine and jet fuel production pathways are discussed in chapter 5, alongside other data that was required for the latter part of this study. The answer to sub-question 3, 4 and 5 is provided in chapter 6 of this study. Finally, chapter 7 provides a discussion on the results whereafter the most important conclusions are drawn in chapter 8.

2. Methodology

This chapter provides a description and substantiation of the methodologies that were used to answer the research questions. It starts with a description of the OPERA model which was pivotal to answering sub-question 3 through 5. Taking the boundaries of OPERA into account, the scope of this thesis is discussed in section 2.3. Section 2.4 describes how the past and future Dutch demand for marine and jet fuels was determined. Importantly, this section also includes a description of the allocation approach that was used to determine which amount of IBF demand the Netherlands could be held accountable for. Furthermore, the GHG reduction targets belonging to each of the three policy scenarios are specified in section 2.5.

2.1. Model description

OPERA (Option Portfolio for Emissions Reduction Assessment) is a bottom-up techno-economic linear programming model developed at ECN part of TNO in the modelling environment AIMMS. The scope of the model includes all processes that contribute to the Dutch national GHG emissions according to the IPCC guidelines for national greenhouse gas inventories (IPCC, 2006) with a focus on energy related processes. Besides energy related GHG emissions the model thus includes GHG emissions from industrial processes and product use, agriculture, forestry and other land use and waste (hereafter referred to as non-energy related emissions) but does not include GHG emissions from land use, land use change and forestry. A general overview of the model structure is shown in figure 2 and explained below. A journal article with additional information about the OPERA model has recently been submitted but is not yet available. In the meantime, the most complete overview of OPERA so far can be found in de Joode et al. (2016).

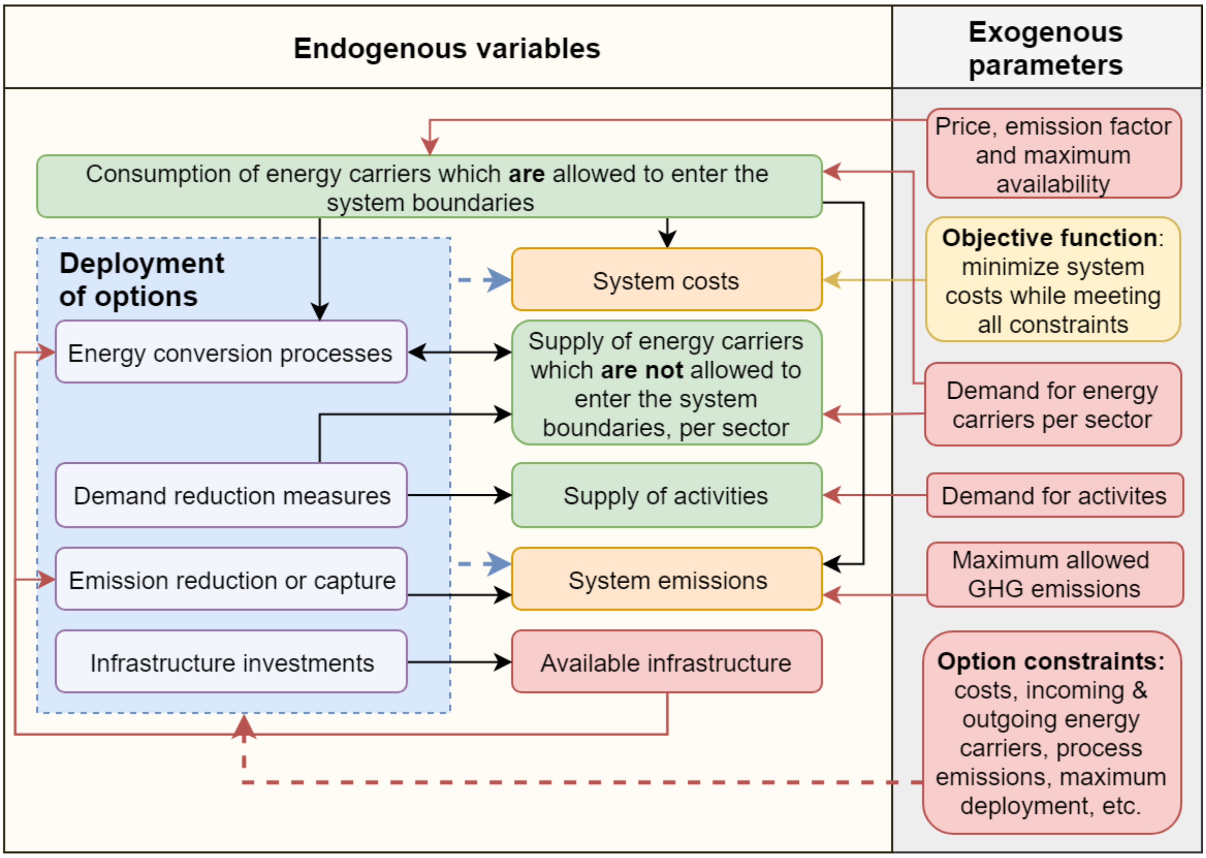

Figure 2: general overview of the OPERA model. For a given year, the model determines which options (blue boxes) have to be deployed in order to provide the required energy carriers & activities (green boxes) against minimal costs while not exceeding the maximum allowable emissions. Boxes in red represent the model constraints.

For a given year, the objective of OPERA is to determine which set of *options* has to be deployed in order to meet the Dutch demand for *energy carriers* and *activities* at minimal costs, while also remaining within all of the systems *constraints*.

Energy carriers refer to energy contained in forms such as natural gas, electricity and diesel. Some energy carriers[2] are allowed to enter the system by being 'bought' which represents them being domestically produced (e.g. mining of fossil fuels and cultivation of biomass) or imported from abroad. Other energy carriers[2] cannot simply be bought but instead have to be produced from within the system through energy conversion processes. An example: the residential sector in OPERA has a demand for the energy carrier 'heat' which cannot directly be bought by the system. Instead natural gas can be bought which is then converted into heat in residential gas boilers. The future final demand for energy carriers in OPERA has been exogenously determined for individual sectors of the Dutch economy and corresponds to that of the baseline scenario in the Dutch energy outlook *Nationale Energieverkenning* (Schoots et al., 2016).

In some cases demand is difficult to describe as a demand for energy carriers and is described as a demand for *activities* instead. Examples include the demand for passenger transport (in tonne-kilometre), the production of ammonia and the emission of CH_4 in agriculture. Like the demand for energy carriers, the future demand for activities in a given year has been exogenously determined before it was added to OPERA.

To meet the demand for energy carriers and activities OPERA has a large variety of *options* at its disposal. Most of these options involve the conversion of energy carriers into other energy carriers or activities. Examples include the abovementioned conversion of natural gas into heat in residential gas boilers or the consumption of gasoline in internal combustion engine vehicles to provide passenger transport. Options may also reduce the demand for energy carriers or activities, e.g. through investing in insulation in houses. Other examples of options include GHG reducing options such as carbon capture and storage (CCS) or options representing possibly necessary infrastructure investments. Options have certain costs, incoming & outgoing energy carriers and process emissions associated with them and OPERA uses this information to weight the options against each other.

The systems *constraints* refer to a range of conditions that the model has to comply with. These include the condition that the demand for energy carriers and activities is met, that the deployment of options is within their maximum potential, that no energy carriers are consumed beyond their maximum availability and that the total GHG emissions of the system do not exceed the target set by the user.

Once a combination of options is found that results in compliance with all of the systems constraints, the costs of the deployed options and bought energy carriers are added together which results in the total system costs. Multiple combinations of options are tried with the combination resulting in the lowest system costs coming out as the best solution. OPERA is a myopic cost-optimization model whose foresight is limited to the individual modelled year. Because of this, path-dependency (e.g. due to previously installed infrastructure or technological learning) is not reflected in the results.

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[2] Energy carriers that are allowed to enter the system (be 'bought') are: coal, cokes, crude oil, LPG, natural gas, uranium, biomass (in various forms), waste, environmental heat, geothermal heat, wind and solar irradiation. Some examples of energy carriers that have to be produced within the system are: heat, diesel, biodiesel and hydrogen. Electricity is a special case since it in principle has to be produced within the system although a predetermined amount is imported or exported each hour of the year.

Because supply has to equal demand not just annually but at any moment during the year OPERA bases its calculations on an hourly time resolution. This is primarily important for the supply and demand of electricity which is difficult to store. The model is however not capable of running all 8760 hours of a the year in explicit time steps since this would result in extremely long computation times. Instead, individual hours are grouped together into *timeslices* in which the conditions of the system are expected to be somewhat similar. In this research the 8760 hours of a year are grouped together into 32 timeslices based on the season in which the hour occurred and the fact if the hour occurred during day-time or night-time

2.2. Model adjustments

To be able to carry out this research several adjustments had to be made to OPERA. The most important adjustments are listed below:

1. A demand for marine fuels from international shipping and a demand for jet fuels from international aviation were added to the model in the form of two new activities. The magnitude of this demand in 2030 & 2050 was calculated exogenous from the model (see chapter 3 & 4).
2. Four new energy carriers were added to the model. These are fossil heavy fuel oil (HFO) and renewable marine fuel which could provide the demand for marine fuels from international shipping and fossil jet fuel and drop-in renewable jet fuel which could provide the demand for jet fuels from international aviation.
3. Options were added that represent the production of fossil HFO and jet fuel and renewable marine fuel and drop-in jet fuels through various energy conversion processes. These include both fossil and biobased conversion pathways. The addition of these options also meant that data about their costs and incoming and outgoing energy carriers was added. This data is discussed in chapter 5.
4. Two new kinds of emissions were added to the model: GHG emissions resulting from the combustion of marine fuels and GHG emissions resulting from the combustion of jet fuels. This allowed a separate target for the GHG emissions from marine and jet fuels to be set, which was necessary for answering sub-question 4.

2.3. Research scope

There are several limitations to this research many of which result from the scope of the OPERA model. Since these limitations determine how the results of this research should be interpreted they are discussed below as well as in the discussion.

This research focusses on the years 2030 and 2050 due to their importance in the context of Dutch and international climate policy targets. These years are viewed in isolation meaning that the ‘optimal solution’ found by the model is only valid given the data it was provided for that year. An implication of this is that the model does not take the presence of previously installed infrastructure into account. It also does not endogenously consider the effects of technological learning on the costs of options. Including technological learning would be difficult to include in a national model anyways given that technological learning is usually a global process. The consequence of this is that the optimal solution found for 2030 might not be on the right path towards an optimal solution for 2050.

Increased consumption of energy carriers that are allowed to be bought by the system only increase the systems emissions by an amount equal to the emission factor of these energy carriers upon combustion. Indirect emissions or process emissions associated with the extraction and transportation of these energy carriers (which often occur outside of the Dutch borders) are not included in this emission factor. The domestic part of these indirect and process emissions are instead incorporated into the model as an exogenously calculated value. The implication of this is that the model assumes these emissions to be constant and unaffected by the amount and types of energy carriers it decides to buy.

The Netherlands is largely represented as a closed system with the exception of the energy carriers that are allowed to be bought by the system. An implication of this is that energy carriers such as fossil jet fuel and biodiesel must be produced within the Dutch borders while in reality these could also be imported from abroad.

In this research the demand for marine fuels can only be fulfilled by a supply of HFO or renewable marine fuels while the demand for jet fuels can only be fulfilled by a supply of fossil jet fuels or renewable drop-in jet fuels. In the case of jet fuels this is a good representation of reality but in the case of marine fuels marine gasoil and LNG are also viable options (CBS, 2018f). These were left out to limit the complexity of the research.

Finally, the techno-economic nature of OPERA means that important social factors were often not included in the research. If Dutch residents would, for example, be unwilling to participate in the deployment of heat pumps in their homes this would restrict the options to reduce GHG emissions in the residential sector in a way that is not currently foreseen by the model. In other cases such as the potential of nuclear power and onshore wind social factors were taken into account by assuming that the maximum future deployment of these options is limited.

2.4. Projecting the marine and jet fuel demand

Based on statistics and projections from a variety of publicly available sources, the past and future demand for marine and jet fuels by the Netherlands is calculated in chapters 3 & 4. Inherent to this calculation is the selection of an *allocation approach* whereby a portion of the global demand for marine and jet fuels is placed under the responsibility of the Netherlands. In the remainder of this research, the marine and jet fuel demand that is allocated to the Netherlands will be referred to as the *Dutch* demand for marine & jet fuels. Possible allocation approaches and the approach that was applied in this research are discussed below.

The regulation of GHG emissions from international shipping and aviation requires an allocation approach whereby the responsibility for the emissions is fairly shared amongst the responsible countries. Several possible allocation approaches have been identified in the past. But which option is most suitable has been the subject of much debate and remains currently undecided upon (Romera, 2016). In 1996 the UNFCCC proposed a range of available options (United Nations, 1996). These are:

- allocation by the country in whose territory the emissions occur;
- allocation in proportion to the countries total national emissions;
- allocation by the country where the vessel or aircraft is registered;
- allocation by the nationality of the transporting company or operator;
- allocation by the country where the bunker fuels are sold;
- an allocation approach based on the departure, destination or origin of passengers & freight.

In this research, three criteria were considered decisive for choosing the appropriate allocation approach:

1. the extent to which the activity of the residents in a country (that is their consumption, production and movement) caused the transport to take place;
2. the extent to which a country benefitted economically from the transport taking place;
3. the possibility of carrying out the allocation approach with publicly available statistics.

Allocation by the country in whose territory the emissions occur is unsuitable because vessels and aircrafts often merely pass through a countries territory without that country causing the transport to take place or benefitting from it. Additionally a large portion of emissions occur in international waters belonging to no single country. Allocation in proportion to a countries total national emissions does not reflect the extent to which countries benefit from the transport taking place and would greatly disadvantage landlocked countries without seaports. Allocation based on the country in which a vessel or airplane is registered, or by the nationality of its owner or operating country is also unsuitable. This is because neither the country of registration, ownership or operating company properly reflects the country that is responsible for the transport taking place (Heitmann & Khalilian, 2011). Per illustration, more than half of global freight in 2017 was transported by cargo vessels registered in Panama, Liberia, the Marshall Islands and Hong Kong (UNCTAD, 2017). Finally, allocation based on the country in which the fuel was sold also seems unviable. This is especially true for marine fuels since cargo vessels bunker a disproportionally large amount of fuel in countries with low fuel prices such as Singapore and the Netherlands.

The best remaining option seems an allocation approach based on the departure, destination or origin of transported passengers and freight. Such an approach has previously been considered impractical due data restrictions (United Nations, 1996). However, recent measurement programs by the IMO & ICAO and relatively detailed statistics in the Netherlands now make this allocation approach feasible. Specifically, the following emissions from international shipping and aviation were allocated to the Netherlands in this research:

- *50% of the emissions from the transport of all Dutch imports and exports, from first sea- or airport of departure or to final sea- or airport of arrival (thus including intermediate stops).*
- *50% of the emissions from the transport of passengers at Dutch airports (both national and international passengers), from last airport of departure or to next airport of arrival.*

The emissions from international passenger transport by ship were deemed insignificant compared to those of freight transport and were therefore excluded from the research. To further clarify which emissions were allocated to the Netherlands figure 3 shows a division of in- and outgoing transport flows. For the transport of freight these are (measured by mass):

- *import for own consumption* (flow 1): all freight destined for consumption by Dutch inhabitants, including resources used in the production processes of companies based in the Netherlands;
- *export of Dutch products* (flow 5): outgoing freight produced by Dutch inhabitants destined for foreign countries;
- *re-export* (flows 2 & 6): freight that, after entering the Netherlands, temporarily changes to a Dutch owner and which later leaves the country without having undergone any significant industrial processing;
- *transit:* freight passing through the Netherlands without undergoing any significant industrial process and without becoming temporarily owned by a Dutch inhabitant. If the freight is transhipped and possibly temporarily stored at a Dutch seaport it is called *transit with transhipment* (flows 3 & 7). If not it is called *transit without transhipment* (flow 4 & 8).

For the transport of passengers, these are:

- arriving passengers with the Netherlands as their final destination (flow 9);
- departing passengers with the Netherlands as their first departure (flow 12);
- passengers using a Dutch airport for transfer, without leaving the airport in the process (flow 10 & 13);
- passengers flying over the Netherlands without landing / departing at a Dutch airport (flows 11 & 14).

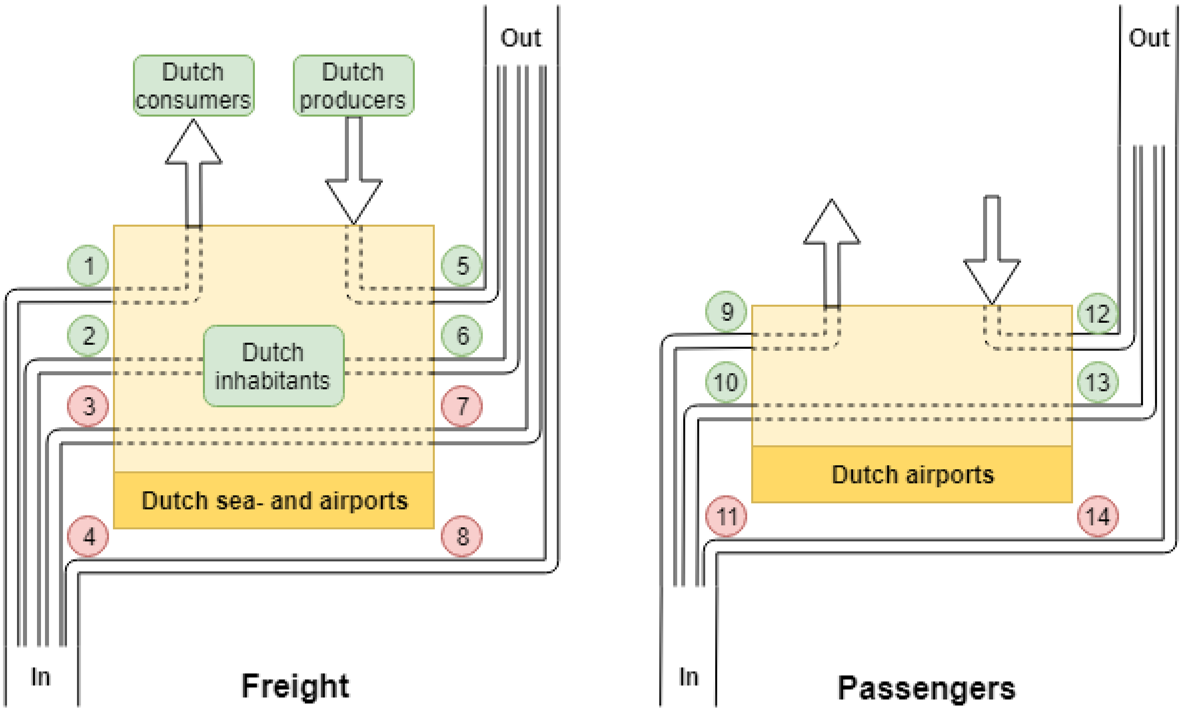

Figure 3: in- and outgoing flows of freight and passengers distinguished in this report. 50% of incoming and outgoing flows displayed in green were allocated to the Netherlands whilst flows displayed in red were ignored. The breakdown of incoming and outgoing flows displayed here was based on that in Dutch statistics (CBS, 2018a-e; De Blois et al., 2009).

The transport flows of which 50% of the emissions (and therefore fuel consumption) were allocated to the Netherlands are displayed in green in figure 3. Emissions from freight transport in transit were not allocated to the Netherlands because they are both produced and consumed abroad, and provide little added value to the Dutch economy (De Blois et al., 2009). Emissions from freight transport for re-export were allocated to the Netherlands because re-exports provide more added value to the Dutch economy (De Blois et al., 2009) and because they are often not separately reported from import for own consumption and export of Dutch products. For the transport of passengers it might have been better to allocate only the emissions from Dutch passengers to the Netherlands, from the first airport of departure or to the final airport of arrival (thus including intermediate stops). This was not possible however with the available statistics.

For the remainder of this report, *import & export* refer to the total mass of import for own consumption, export of Dutch products and re-export (flows 1, 2, 5 & 6). Re-export is counted double because this includes both an incoming and outgoing transport flow. *Transhipment* refers to the sum of all incoming and outgoing freight at Dutch sea- or airports (flows 1-3 & 5-7). Re-export and transit with transhipment are counted double because these include both incoming and outgoing transport flows. Although only traffic resulting from imported and exported freight was allocated to the

Netherlands in this research, information applicable to transhipment was often used to predict growth rates because more detailed information was unavailable.

For the remainder of this report *import, export & transhipment* refer to the *mass* of transported freight; *arrivals & departures* refer to the *amount* of passengers transported and *traffic* refers to the *amount of work* required to transport passengers or freight. Passenger traffic is measured in revenue passenger kilometres (RPK) and excludes non-paying passengers such as flight attendants. Freight traffic is measured in revenue tonne kilometres (RTK) and excludes the mass of infrastructure such as containers or the airplane.

2.5. Maximum allowable GHG emissions

Sub-question 3, 4 & 5 of this research reflect different policy scenarios with regards to the inclusion of emissions from international shipping and aviation in the Dutch GHG reduction targets. The maximum allowable GHG emissions thus differ per sub-question. Additionally a *separate* target for the emissions from international shipping and aviation may or may not be set. How the GHG emission targets differ per sub-question is described below. An overview of the maximum allowable GHG emissions (in million tonnes (Mt) CO_2-eq) per sub-question is shown further on in the report in section 5.3.

Sub-question 3 explores a reference scenario in which the current policy remains unchanged. This means that the emissions from international shipping and aviation are ignored while the remaining national emissions in reference to 1990 have to be reduced by 49% in 2030 and 95% in 2050. The Dutch national GHG emissions (excluding international shipping and aviation) were 224 Mt CO_2-eq in 1990 (UNFCCC, 2017). The maximum allowable GHG emissions in this sub-question are therefore set at 114Mt CO_2-eq in 2030 and 11.2 Mt CO_2-eq in 2050.

In the scenario described in sub-question 4 the national GHG emission targets are the same as those in sub-question 3. Again, the emissions from international shipping and aviation are not included in the national emissions. However, an additional separate target for the emissions from international shipping and aviation is implemented. This target is set in accordance with the ambitions of the IMO & ICAO. The ambition of the IMO is to *peak emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008* (IMO, 2018). The ambition of the ICAO is that GHG emissions from international aviation should stabilize from 2020 onwards (ICAO, 2013). In sub-question 4 the IMO and ICAO ambitions were implemented as follows:

1) The Dutch emissions from international shipping and aviation are allowed to peak in 2020 at a level that would be expected under business-as-usual conditions in that year.
2) The Dutch emissions from international shipping should decrease linearly between 2020 and 2050 until the 2050 emissions are 50% of what they were in 2008. By making this assumption, a target for 2030 could be deduced.
3) The Dutch emissions from international aviation in 2030 and 2050 should at most be equal to those expected under business-as-usual conditions in 2020.

In the previous, *business-as-usual* means that the demand for marine fuels is met exclusively by fossil HFO while the demand for jet fuels is met exclusively by fossil jet fuel. Accordingly, the GHG emissions under business-as-usual conditions were calculated by multiplying the projected demand for marine and jet fuels with the emission factors of HFO and fossil jet fuel upon combustion.

Finally, sub-question 5 explores a scenario in which the emissions from international shipping and aviation *are* included in the total national emissions. The GHG reduction targets (49% by 2030 and 95% by 2050, in reference to 1990) remain unchanged. A large amount of extra emissions thus have to be reduced. However, the emissions from international shipping and aviation are now also included in the 1990 reference emissions. Therefore the maximum allowable GHG emissions (in Mt CO_2-eq) in 2030 & 2050 increase as well. No separate target for the emissions from international shipping and aviation exists. This means that the extra required GHG reduction may be achieved by substituting fossil marine and jet fuels with renewable alternatives, by making additional commitments to reduce GHG emissions in other sectors of the Dutch economy, or by a combination of both.

3. Marine fuel demand

This chapter describes the process by which the Dutch demand for marine fuels was calculated. The marine fuel demand was calculated for 6 different years: 2016, because this is the most recent year for which statistics were available; 2030 & 2050, because the fuel demand in those years had to be added to the model; and 1990, 2008 & 2020, because the GHG emissions from marine fuels needed to be determined in those years in order to set appropriate GHG reduction targets for sub-question 4 & 5.

The calculation process and used information sources are summarized in figure 4 below. Each of the calculation steps shown in figure 4 is discussed in separate sections of this chapter.

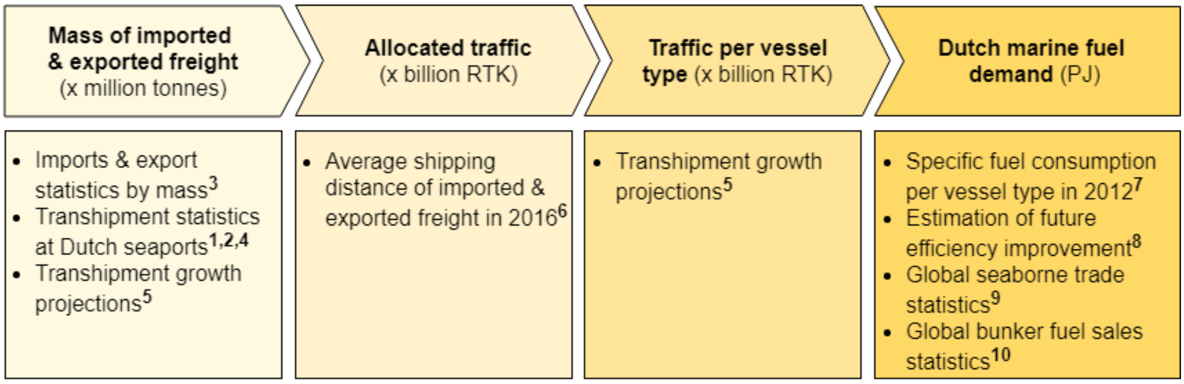

Figure 4: schematic overview of the process by which the allocated demand for marine fuels was calculated. The superscripted numbers refer to the following sources: 1: CBS (2018a); 2: CBS (2018b); 3: CBS (2018c); 4: CLO (2018); 5: Port of Rotterdam (2011); 6: Chris de Blois, personal communication, June 1st 2018; 7: Smith et al. (2015a); 8: Smith et al. (2015b); 9: Buhaug et al. (2009).

This chapter contains formulas to clarify the calculation displayed in figure 4. The meaning of the symbols in these formulas are shown below:

M	total mass of imported and exported freight at all Dutch seaports (Mt)
$TRAN$	total mass of transhipped freight (Mt)
W	freight traffic (billion RTK) allocated to the Netherlands (the Dutch demand)
E	total marine fuel demand (PJ) allocated to the Netherlands (the Dutch demand)
r	annual growth rate (% per year)
d	average shipping distance of imported and exported freight (km)
fc	specific fuel consumption (MJ / RTK)
PoR	Port of Rotterdam
all	all Dutch seaports

3.1. Imports and exports at Dutch seaports

3.1.1. Past imports and exports

The total volume of imported and exported freight in 2016 was retrieved from CBS (2018c), who calculated the mass of all freight imported and exported through sea shipping at Dutch seaports between 2007 – 2016 (figure 5). Freight imports and exports before 2007 were not recorded. Instead, statistics about transhipment volumes from CBS (2018a), CBS (2018b) and CLO (2018) were used (figure 6) in this research. To calculate the volume of imported and exported freight in 1990 it was assumed that imports and exports at Dutch seaports increased at the same rate as total transhipment between 1996 and 2007. For the period 1990 – 1996 only transhipment at the Port of Rotterdam was recorded. Imports and exports at Dutch seaports were therefore assumed to have increased at the same rate as total transhipment at the Port of Rotterdam. This assumption is justified by that fact that between 1996 – 2017, 74% to 79% of total national transhipment through sea shipping occurred in the Port of Rotterdam. However, some deviation from the actual import & export growth rate is possible since imports and exports might have grown at a different rate than total transhipment in the period 1990 – 1996.

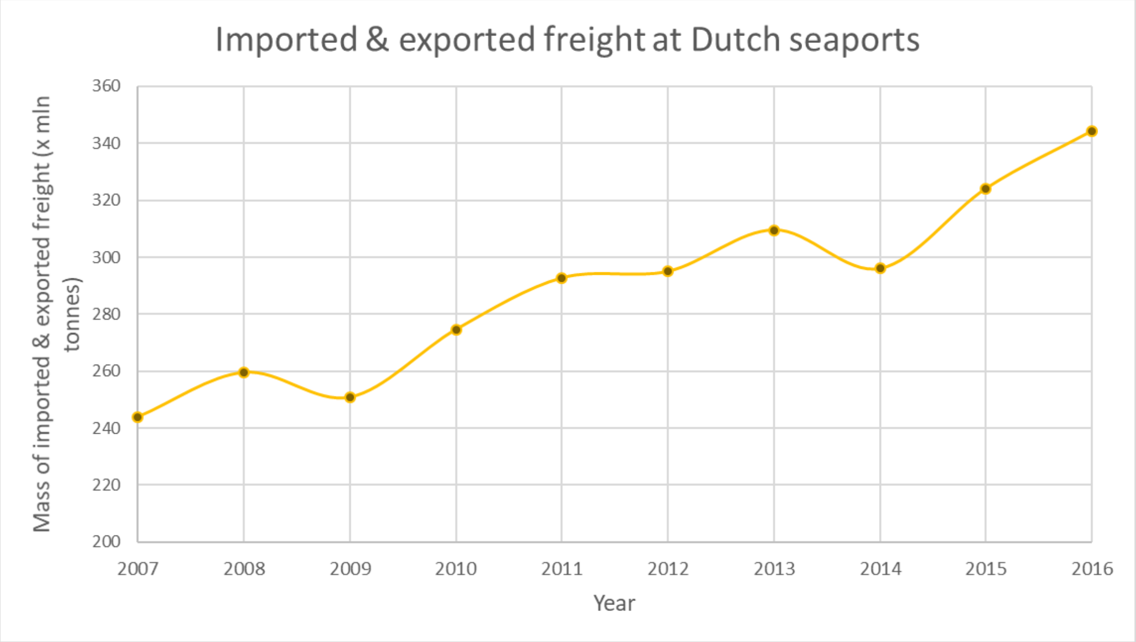

Figure 5: mass of imported and exported freight at Dutch seaports between 2007 and 2016.

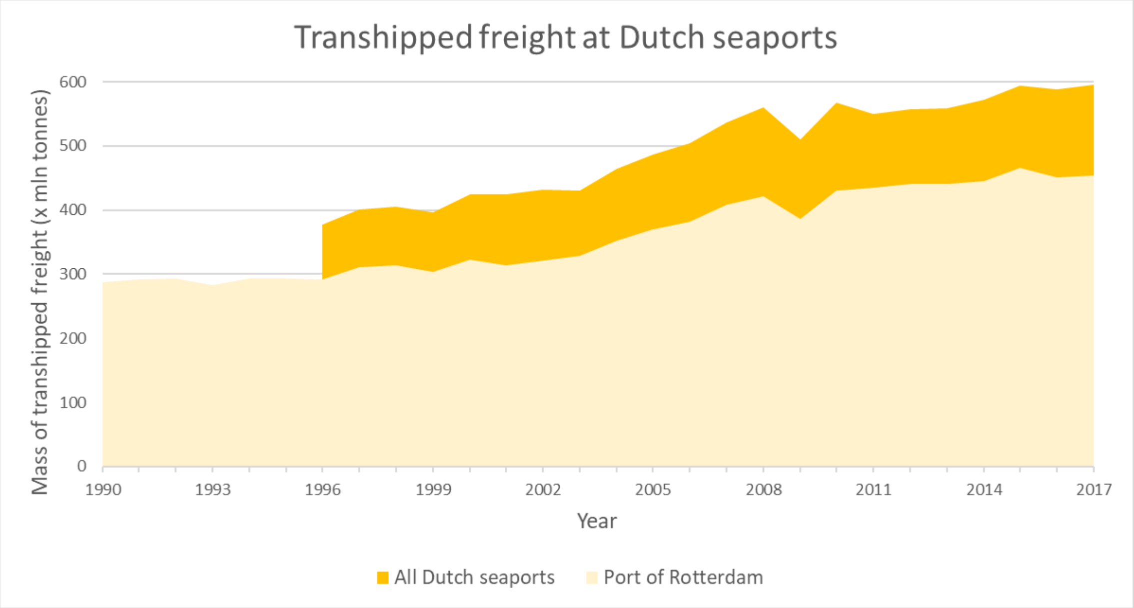

Figure 6: mass of transhipped freight from international sea shipping at Dutch seaports between 1990 and 2017. Total transhipment between 1990 and 1996 was not recorded.

The historical data was used to calculate the mass of imported & exported freight at Dutch seaports in 1990, 2008 & 2016:

$M_{2016} = \mathbf{344.4}$ **million tonnes** (from CBS (2018c))

$M_{2008} = \mathbf{259.5}$ **million tonnes** (from CBS (2018c))

$$M_{1990} = M_{2007} \cdot \frac{TRAN_{PoR,1990}}{TRAN_{PoR,1996}} \cdot \frac{TRAN_{all,1996}}{TRAN_{all,2007}} = 243.9 \cdot 0.9853 \cdot 0.7044 = \mathbf{169.3}\ \textbf{million tonnes}$$

3.1.2. Projected imports & exports

To forecast the future mass of imported and exported freight at Dutch seaports the statistics from CBS (2018b) were combined with growth projections for freight transhipment at the Port of Rotterdam (Port of Rotterdam, 2011). In the absence of a study projecting the growth of only imported and exported freight, the growth projections from Port of Rotterdam (2011) were assumed representative. However, it is not unlikely that imports and exports would grow at a different rate than total transhipment. It is also possible that transhipment at all Dutch seaports would grow at a different rate than transhipment at the Port of Rotterdam.

The Port of Rotterdam study forecasts the transhipment of 16 categories of goods at the port until 2040. The study includes 4 scenarios of which the *European trend* scenario is most in line with the assumptions underlying OPERA's baseline scenario. The European trend scenario is based on the continuation of current policy combined with moderate economic growth and is used in many European policy studies (Port of Rotterdam, 2011). Table 1 shows some of the main assumptions underlying the European trend scenario. The reported results of the scenario are shown in table 2.

Table 1: main assumptions underlying the European Trend scenario in the Port of Rotterdam study (Port of Rotterdam, 2011).

GDP growth	**2000-2010**	**2010-2020**	**2020-2030**	**2030-2040**
Netherlands	1.4%	1.8%	1.5%	1.3%
EU-15	1.95%	2.13%	1.54%	not mentioned
Oil price ($/bbl)	**2005**	**2030**	**2050**	
Europe	55	58	68	
Primary energy consumption (Mtoe)	**2005**	**2030**	**2050**	
EU-15	1960	2080	2180	
% oil	41%	34%	26%	
% coal	16%	15%	14%	
% biomass	4%	8%	9%	

Table 2: past (2008) and projected (2020; 2030; 2040) transhipment of freight from international shipping at the Port of Rotterdam. The values in this table are the results of the European trend scenario as reported in Port of Rotterdam (2011).

Freight category	**Mass of transhipped freight from international shipping (Mt)**			
Wet bulk	*2008*	*2020*	*2030*	*2040*
Crude oil	100	96	96	81
Mineral oil products	59	67	76	88
LNG	0	20	23	26
Chemical products	26	29	34	40
Vegetable oils	9	11	13	14
Dry bulk				
Agricultural bulk	10	8	7	5
Iron ore	43	40	34	27
Coal	29	40	39	37
Dry biomass	0	2	3	4
Other dry bulk	12	14	14	14
Break bulk / General cargo				
Containers, total	107	190	267	338

Direct Deep Sea	64	114	164	207
Transhipment	27	57	80	105
Short Sea	16	18	23	26
Steel	4	12	16	20
Roll-on-roll-off	17	22	26	29
Other general cargo	3	3	3	3
Total Rotterdam	**420**	**554**	**650**	**727**

In the European Trend scenario, increasing demand for personal and freight transport is largely met by fuel efficiency improvements, thus not leading to a significant increase of fuel demand by the European transport sector. Fossil oil-based fuels are expected to be increasingly substituted by biofuels and LNG. This results in a decrease of crude oil transhipments, while transhipments of LNG and mineral oil products both show large increases. Besides fuel substitution, an important driver for the increasing transhipment of LNG and mineral oil products is the increasingly important hub function of the port of Rotterdam. Since mineral oil products are expected to be increasingly produced outside of Europe, imports of these products by other European countries via the Port of Rotterdam will rise (Port of Rotterdam, 2011).

By far the largest portion of projected transhipment growth is caused by the steep increase of container transport at the Port of Rotterdam. Although container transport in North-Western Europe is expected to grow less quickly than in the past, the total mass of freight transhipments in containers at the Port of Rotterdam is still projected to triple over the period 2008 – 2040. The relatively good market position of the Port of Rotterdam compared to other ports in the region with the development of the 'tweede Maasvlakte', good connections with the European hinterland and the ports capability to handle very large container ships will increase the ports market share for container transhipment in the region (Port of Rotterdam, 2011).

The steel industry is expected to grow in emerging countries causing blast furnaces in North-Western Europe to shut down. This in turn decreases iron ore transhipment while steel imports increase. The increase of coal transhipment from 2008 – 2020 can be mostly attributed to the construction of two new coal-fired power plants in the Port of Rotterdam in 2016 (Port of Rotterdam, 2011).

The projections in table 2 were used to estimate the annual growth rate of freight imports and exports at Dutch seaports between 2008 & 2050. Since Port of Rotterdam (2011) included no results for the period 2040 – 2050 the annual growth rate in this period was calculated by extending the projected trend in the period 2020 – 2040. So for example, since the Port of Rotterdam study showed an annual growth rate for crude oil transhipment of 0% in the period 2020 – 2030 and -1.7% in the period 2030 – 2040, an annual growth rate of -3.4% in the period 2040 – 2050 was assumed. The resulting growth rates are shown in table 3.

Table 3: annual growth rates used to forecast the mass of imported & exported freight at Dutch seaports in 2030 & 2050.

Period	Annual growth rate
2008 - 2020	2.334%
2020 - 2030	1.611%
2030 - 2040	1.126%
2040 - 2050	0.589%

Finally, the mass of imported and exported freight at Dutch seaports in 2020, 2030 & 2050 were calculated using the formulas below:

$$M_{2020} = M_{2016} * \left(1 + r_{TRAN,2008-2020}\right)^{(2020-2016)} = 344.4 * 1.02334^{4} = \mathbf{381.1\ million\ tonnes}$$

$$M_{2030} = M_{2020} * \left(1 + r_{TRAN,2020-2030}\right)^{(2030-2020)} = 381.1 * 1.01611^{10} = \mathbf{447.2\ million\ tonnes}$$

$$M_{2050} = M_{2030} * \left(1 + r_{TRAN,2030-2040}\right)^{(2040-2030)} * \left(1 + r_{TRAN,2040-2050}\right)^{(2050-2040)}$$

$$= 447.2 * 1.01126^{10} * 1.00589^{10} = \mathbf{530.4\ million\ tonnes}$$

3.2. Dutch traffic demand from international shipping

Marine fuel consumption has a clearer physical relationship to the amount of traffic (in RTK) than to the mass (in tonnes) of imported and exported freight. CBS estimated that the average distance covered by freight imported or exported via international sea shipping was 8626 km in 2016 (Chris de Blois, personal communication, June 1st, 2018). This included the entire journey from first seaport of departure and to last seaport of arrival, so including any intermediate port calls. The estimation by CBS was based on the international flow of freight to and from the Netherlands as published in CBS (2018c). An estimation per freight category or for any year other than 2016 was not freely available. The average shipping distance of 8626 km in 2016 was therefore used in the traffic calculations for 1990, 2008, 2016, 2020, 2030 and 2050, even though a variation of average shipping distance over the years due to changing importing & exporting countries seems plausible.

Additionally the allocation method was applied by which the Netherlands is only held accountable for 50% of the imported and exported freight. The resulting traffic calculations are shown below:

$$W_{1990} = 0.5 * M_{1990} * d_{2016} = 0.5 \cdot 169.3 \cdot 8626 \cdot 10^{3} = \mathbf{730\ billion\ RTK}$$

$$W_{2008} = 0.5 * M_{2008} * d_{2016} = 0.5 \cdot 259.5 \cdot 8626 \cdot 10^{3} = \mathbf{1119\ billion\ RTK}$$

$$W_{2016} = 0.5 * M_{2016} * d_{2016} = 0.5 \cdot 344.46 \cdot 8626 \cdot 10^{3} = \mathbf{1485\ billion\ RTK}$$

$$W_{2020} = 0.5 * M_{2020} * d_{2016} = 0.5 \cdot 381.1 \cdot 8626 \cdot 10^{3} = \mathbf{1644\ billion\ RTK}$$

$$W_{2030} = 0.5 * M_{2030} * d_{2016} = 0.5 \cdot 447.2 \cdot 8626 \cdot 10^{3} = \mathbf{1929\ billion\ RTK}$$

$$W_{2050} = 0.5 * M_{2050} * d_{2016} = 0.5 \cdot 530.4 \cdot 8626 \cdot 10^{3} = \mathbf{2288\ billion\ RTK}$$

3.3. Traffic per vessel type

The varying categories of freight imported and exported at Dutch seaports are transported via different types of vessels which have varying specific fuel consumption (fuel consumption per unit traffic). It is therefore useful to know which share of the total traffic between 1990 - 2050 occurred using each type of vessel.

Based on Smith et al. (2015a) six types of vessels are distinguished in this research. Each of the freight categories from Port of Rotterdam (2011) were assigned to one of these vessel types (see table 4). This way the projected transhipment per freight category (as shown in table 2) was used to project the share of traffic provided by each vessel type. The results are shown in figure 7. Since Port of

Rotterdam (2011) mentioned no transhipment growth rates for the periods 1990 - 2008 and 2040 – 2050 these were estimated by extending the trend in the period 2008 – 2040. This is the same approach as was used in section 3.1. to calculate the transhipment growth rate from 2040 - 2050.

Table 4: distribution of freight categories from Port of Rotterdam (2011) over the vessel types from Smith et al. (2015a).

Vessel type	**Freight category**
Oil tanker	crude oil, mineral oil products, vegetable oils
Liquefied gas tanker	LNG
Chemical tanker	chemical products
Bulk carrier	agricultural bulk, iron ore, coal, dry biomass, other dry bulk
Container ship	Containers; direct deep sea, transhipment, short sea
General cargo ship	Steel, roll-on-roll-off, other general cargo

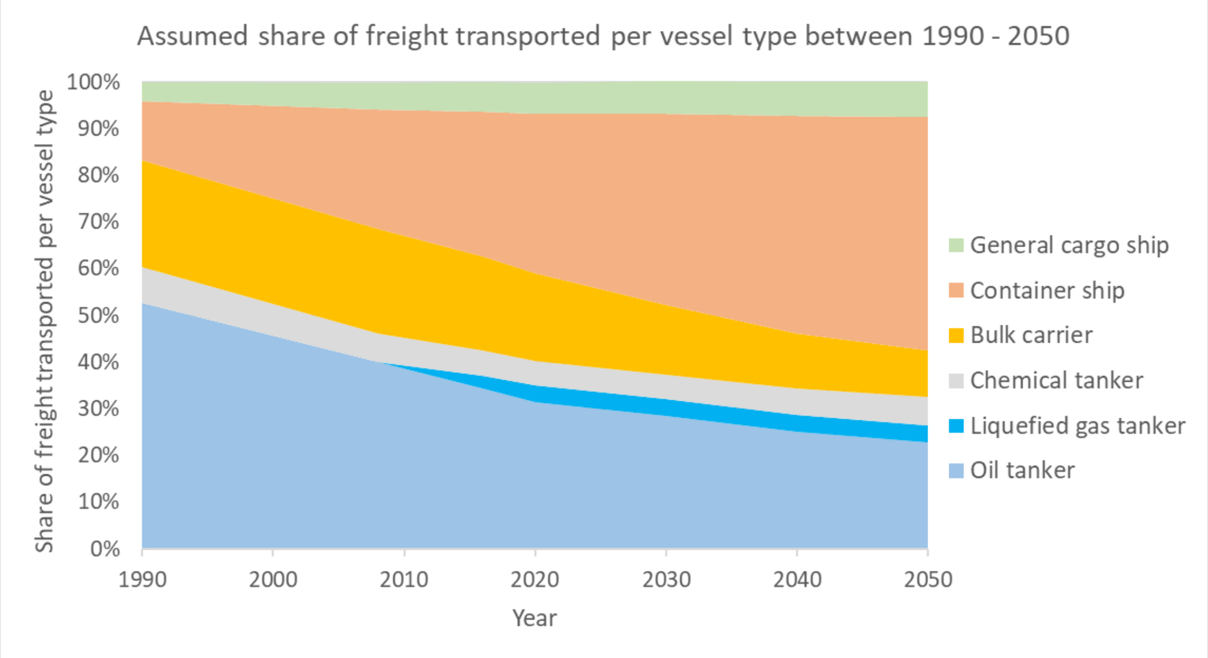

Figure 7: assumed share of freight transported per vessel type.

Figure 7 shows how the decreasing use of fossil fuels and increasing trade with sea containers cause freight transport to shift away from using predominantly oil tankers and bulk carriers towards using predominantly container ships. The consequence of this shift on the marine fuel demand is discussed in section 3.4.

3.4. Final Dutch marine fuel demand

Commissioned by the IMO, Smith et al. (2015a) used large amounts of S-AIS data (from tracking systems on board of sea vessels) to calculate the specific fuel consumption of 7 types of sea vessels. The used dataset covered about 10% of the active world fleet and the resulting calculation included details such as ship size, payload utilisation and shipping speed. The calculated median specific fuel consumption per vessel type in 2012 (the most recent year for which results were available) was used in this research.

The specific fuel consumption per vessel type in 2012 from Smith et al. (2015a) was combined with efficiency improvement estimations until 2050 to forecast the specific fuel consumption per vessel type in 2020, 2030 and 2050. The specific fuel consumption per vessel type in 1990 and 2008 were calculated using information about past efficiency improvements. Figure 8 shows the resulting specific fuel consumption per vessel type and year (2008 & 2020 were not shown in the graph to remain a clear overview). The underlying assumptions on efficiency improvements are discussed in the text below figure 8.

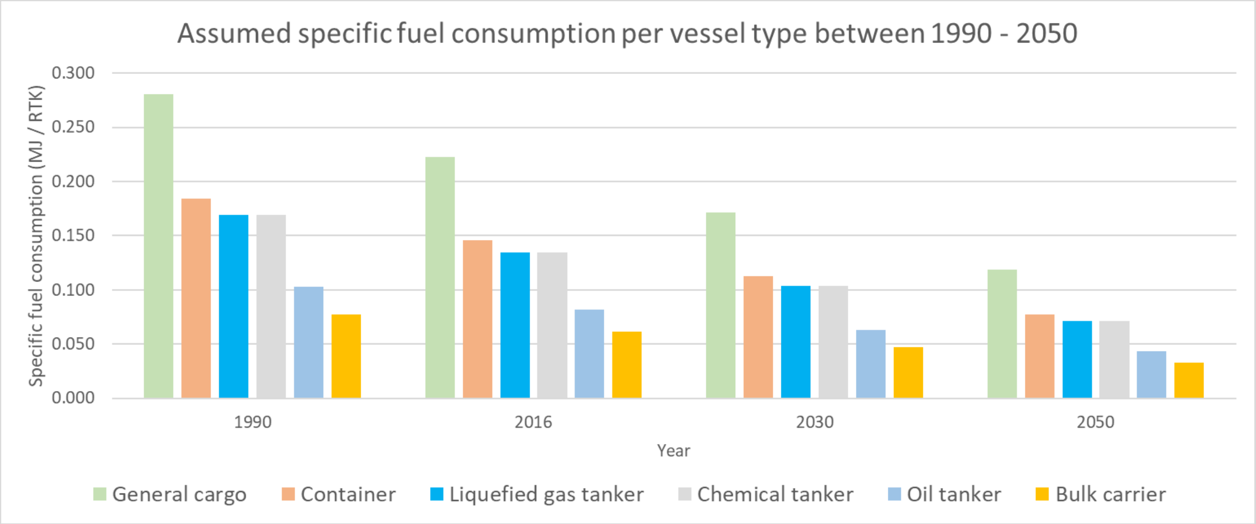

Figure 8: specific fuel consumption per vessel type and year, as used in the calculations.

Bauman et al. (2017) collected information from 150 studies published after 2009 to identify the CO_2 mitigation potential of state-of-the-art technologies and measures in the maritime sector. Figure 9 shows the resulting range of reported reduction potentials for 22 technical and operational measures.

The large range of reported reduction potentials illustrate the low level of agreement among studies, although some of the deviation can be explained by the different reference years that were used to calculate the reduction potentials. Nevertheless, it can be concluded that a large number of practically and economically feasible measures is already available which can lead to significant efficiency improvements. As one example, Bauman et al. (2017) investigated the combined effect of the following measures: vessel size; hull shape; ballast water reduction; hull coating; hybrid power/propulsion; propulsion efficiency devices; speed optimization and weather routing. The combination of these measures would lead to emission reductions of 78% based on 3rd quartile reduction potential values, 55% based on median values or 29% based on 1st quartile values.

The large range of technical reduction potentials combined with uncertainty surrounding factors affecting the actual uptake of technically possible measures (such as environmental policy and oil price) make it nearly impossible to predict the rate of future efficiency improvements in shipping. This research therefore adopts the assumption of the 3rd IMO GHG study that technical and operational efficiency improvements in shipping (thus excluding fuel substitution) will lead to a 50% efficiency improvement over the period 2012 – 2050 (Smith et al., 2015b). Specifically, an annual 1.84% decrease of specific fuel consumption from 2012 – 2050 was assumed to be achieved by technical and operational measures. Lacking more detailed information, it was assumed that the rate of efficiency improvements would be the same for all 6 vessel types.

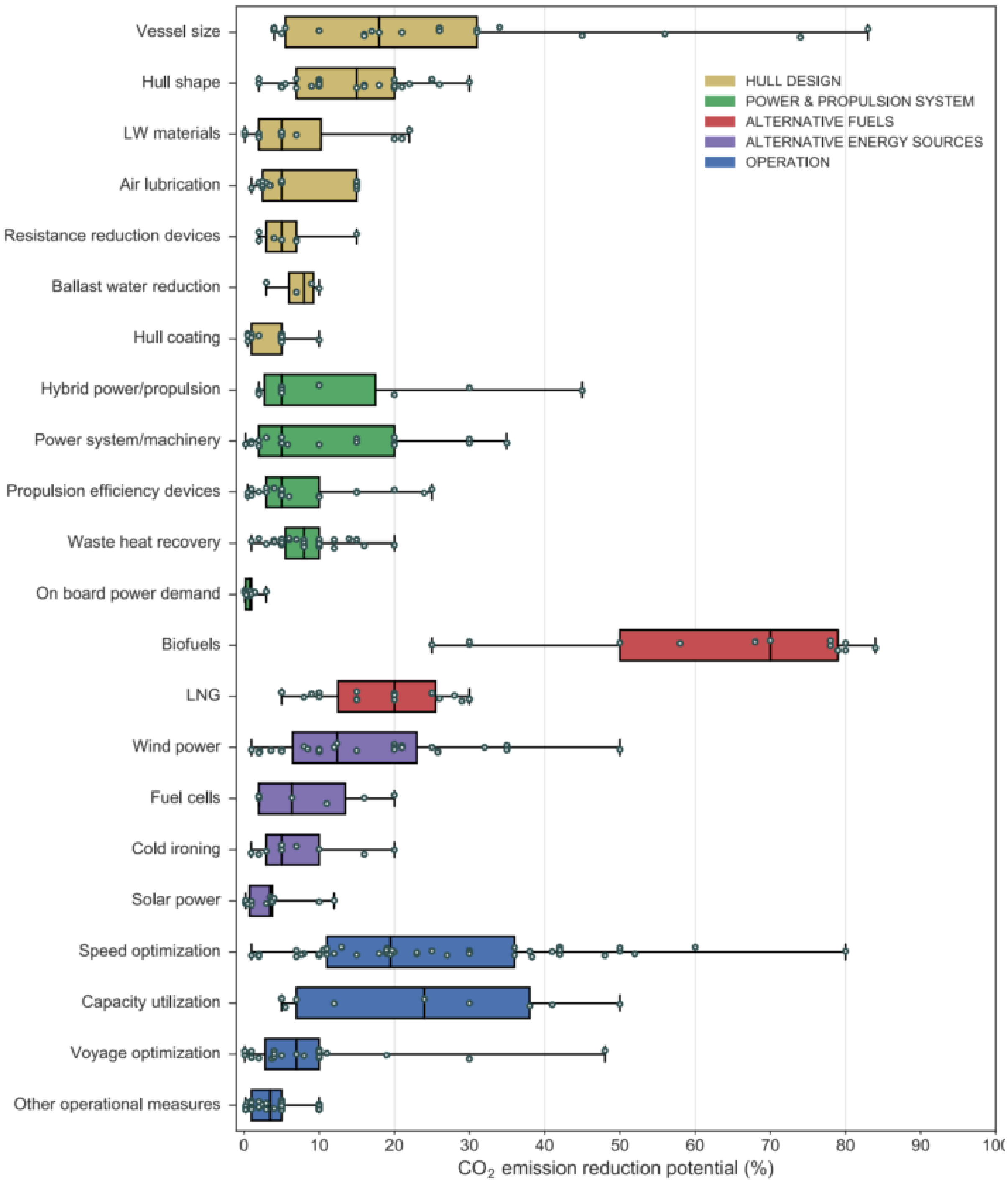

Figure 9: range of reported CO_2 reduction potentials of 22 technical and operational measures, as reported in Bauman et al. (2017).

Buhaug et al. (2009) reported that global seaborne freight traffic increased by 87.1% over the period 1990 – 2007. Global marine fuel bunker sales increased by only 66.0% over that same period (IEA, 2010). From this it was deducted that the past efficiency improvement over the period 1990 – 2007 had been 0.71% per year. For the period 2007 – 2012 this same efficiency improvement was assumed.

The final marine fuel demand could now be calculated as follows:

$$E_{1990} = \sum_{vessel\ type}\left(W_{1990} \cdot share_{vessel\ type,1990} \cdot fc_{vessel\ type,1990}\right) = \mathbf{87.4\ PJ}$$

$$E_{2008} = \sum_{vessel\ type}\left(W_{2008} \cdot share_{vessel\ type,2008} \cdot fc_{vessel\ type,2008}\right) = \mathbf{129.9\ PJ}$$

$$E_{2016} = \sum_{vessel\ type}\left(W_{2016} \cdot share_{vessel\ type,2016} \cdot fc_{vessel\ type,2016}\right) = \mathbf{164.7\ PJ}$$

$$E_{2020} = \sum_{vessel\ type}\left(W_{2020} \cdot share_{vessel\ type,2020} \cdot fc_{vessel\ type,2020}\right) = \mathbf{173.7\ PJ}$$

$$E_{2030} = \sum_{vessel\ type}\left(W_{2030} \cdot share_{vessel\ type,2030} \cdot fc_{vessel\ type,2030}\right) = \mathbf{177.9\ PJ}$$

$$E_{2050} = \sum_{vessel\ type}\left(W_{2050} \cdot share_{vessel\ type,2050} \cdot fc_{vessel\ type,2050}\right) = \mathbf{155.4\ PJ}$$

Figure 10 shows the total fuel consumption per year broken down per vessel type:

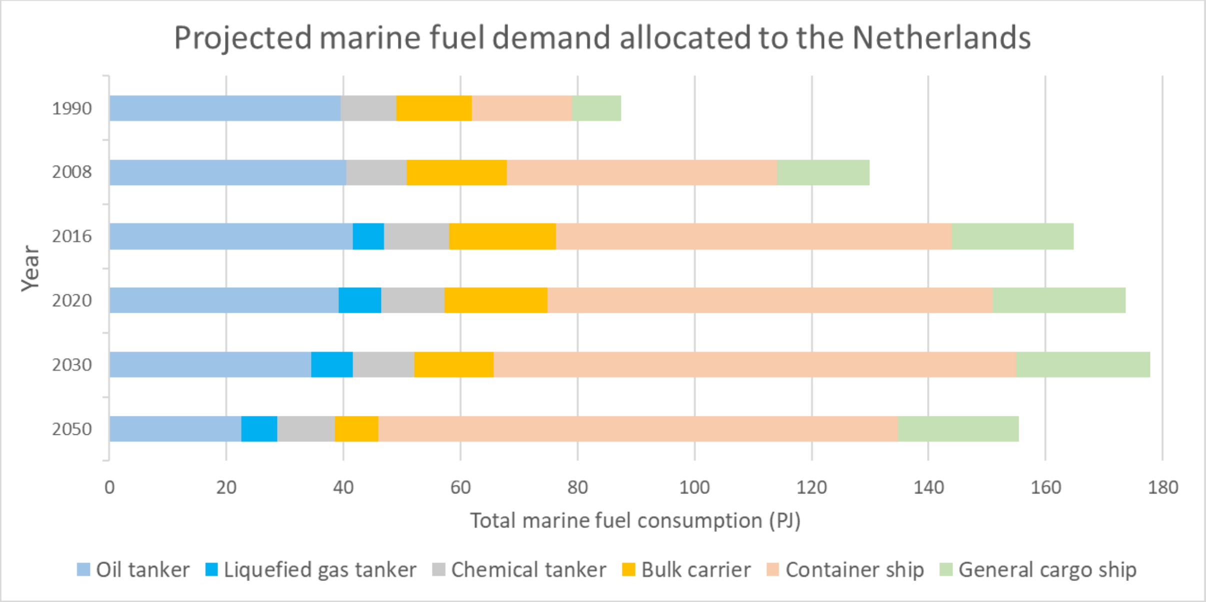

Figure 10: marine fuel demand allocated to the Netherlands.

The results show that compared to 2016, the Dutch demand for marine fuels increases only slightly by 2030 and even reduces somewhat by 2050. This is because large technical and operational efficiency improvements are projected to be made in the future, while the demand growth for sea transport starts to flatten. An increasing share of future freight is projected to be transported by container ships. The relatively high specific fuel consumption of container ships means that the marine fuel demand is higher than it would have been its share of total freight traffic would have remained the same.

The strong historical growth of international sea shipping and the smaller share of freight transported by container ships mean that the marine fuel demand in 1990 and 2008 is much lower than that in 2016, 2030 or 2050. Since the GHG emissions target is defined relative to the emissions in 1990, this translates to a strict target for future emissions.

4. Jet fuel demand

This chapter describes how the Dutch demand for jet fuels was calculated. The jet fuel demand was calculated for 5 different years: 2016, because this is the most recent year for which statistics were available; 2030 & 2050, because the fuel demand in those years had to be added to the model; and 1990 & 2020, because the GHG emissions from jet fuels in those years needed to be determined in order to set appropriate GHG reduction targets for sub-question 4 & 5.

Three forms of air transport are distinguished in this research: passenger transport, freight transported in the belly of passenger aircrafts and freight transported by dedicated freighter aircrafts. The calculation process and most important information sources have been summarized in figure 11. Each of the calculation steps shown in figure 11 are discussed in separate sections of this chapter.

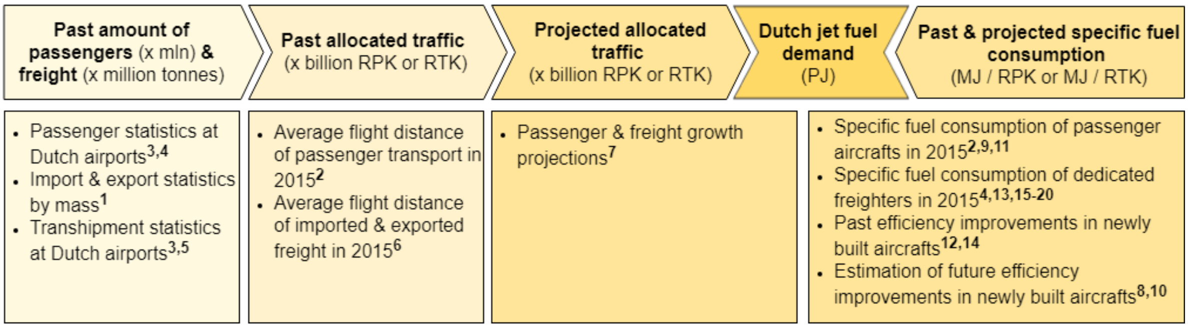

Figure 11: schematic overview of the process by which the Dutch demand for jet fuels was calculated. The superscripted numbers refer to the following sources: 1: CBS (2018c), 2: CBS (2018d), 3: CBS (2018e), 4: Schiphol (2016), 5: Schiphol (2018), 6: Chris de Blois, personal communication, June 1st, 2018, 7: Airbus (2018a), 8: ICAO (2016b), 9: ICAO (2017a), 10: ICAO (2017b), 11: ICAO (2018), 12: EEA (2017a), 13: EEA (2017b), 14: Kharina & Rutherford (2015). 15: Boeing (2018), 16: Airbus (2018b), 17: DHL (2018), 18: Safair (2018), 19: aerospace-technology.com (2018), 20: BAE systems (2004).

This chapter contains formulas to clarify the calculation process displayed in figure 11. The meaning of the symbols in these formulas are shown in the box below:

P	amount of passengers handled, arrivals + departures (millions)
M	mass of imported & exported freight (Mt)
T	mass of transhipped freight (Mt)
W	traffic (billion RPK or billion RTK) allocated to the Netherlands (the Dutch demand)
d	the (average) flight distance km
fc	specific fuel consumption (MJ/RPK or MJ/RTK)
p	passengers
f	freight
fp	freight transported in the belly of passenger aircrafts
ff	freight transported by dedicated freighter aircrafts
all	all Dutch airports

4.1. Past amount of passengers and freight at Dutch airports

4.1.1. Past amount of passengers

The past number of passengers on international flights arriving at or departing from Dutch airports was retrieved from CBS (2018e) and Schiphol (2018). This information is shown in figure 12. The statistics show that the number of passengers at Dutch airports grew fast over the past 15 years, often at more than 10% per year. A small dip occurred during the 2008 economic crisis, but the growing trend quickly returned in the years thereafter. Despite the fact that five airports in the Netherlands offer international flights, the vast majority of passenger transport occurred at Schiphol.

Figure 12: annual amount of passengers at Dutch airports. Statistics for all Dutch airports between 1992 – 1997 were not available and were therefore not included in the figure.

No statistics for passenger transport at Schiphol between 1990 – 1992 or at all Dutch airports between 1990 – 1997 were available. It was therefore assumed that passenger transport at all Dutch airports between 1990 – 1997 grew at the same annual rate as passenger transport at Schiphol between 1992 – 1997; at 10.6% per year. This assumption is not expected to have a significant influence on the results because Schiphol was by far the most important airport between 1990 – 1997. The amount of passengers at Dutch airports were calculated as shown below:

$$P_{all,2016} = \mathbf{70.28\ million\ passengers}\text{ (from CBS (2018e))}$$

$$P_{all,1990} = P_{all,1997} \cdot \left(\frac{P_{Schiphol,1992}}{P_{Schiphol,1997}}\right)^{\left(\frac{1997-1990}{1997-1992}\right)} = 32.07 \cdot \left(\frac{18.71}{31.02}\right)^{7/5} = \mathbf{15.81\ million\ passengers}$$

4.1.2. Past imports and exports

The mass of imported and exported freight at Dutch airports between 2007 – 2016 was retrieved from CBS (2018c) and is depicted in figure 13. The statistics show the volatility of freight imports and exports by air, which decreased fast during the 2008 economic crisis but then almost doubled again between 2009 - 2010.

Imports and exports before 2007 were not recorded. Therefore, to estimate imports & exports in 1990, statistics describing total *transhipment* of freight at Dutch airports from CBS (2018e) & Schiphol (2018) were used as a substitute. These are shown in figure 14. Imports and exports between 1992 – 2007 were assumed to grow at the same rate as total transhipment in that period. For 1990 – 1992 transhipment statistics were also unavailable. Instead, it was assumed that imports & exports between 1990 – 1992 grew at the same annual rate as total transhipment between 1992 – 1997. The resulting calculations are shown below figure 14.

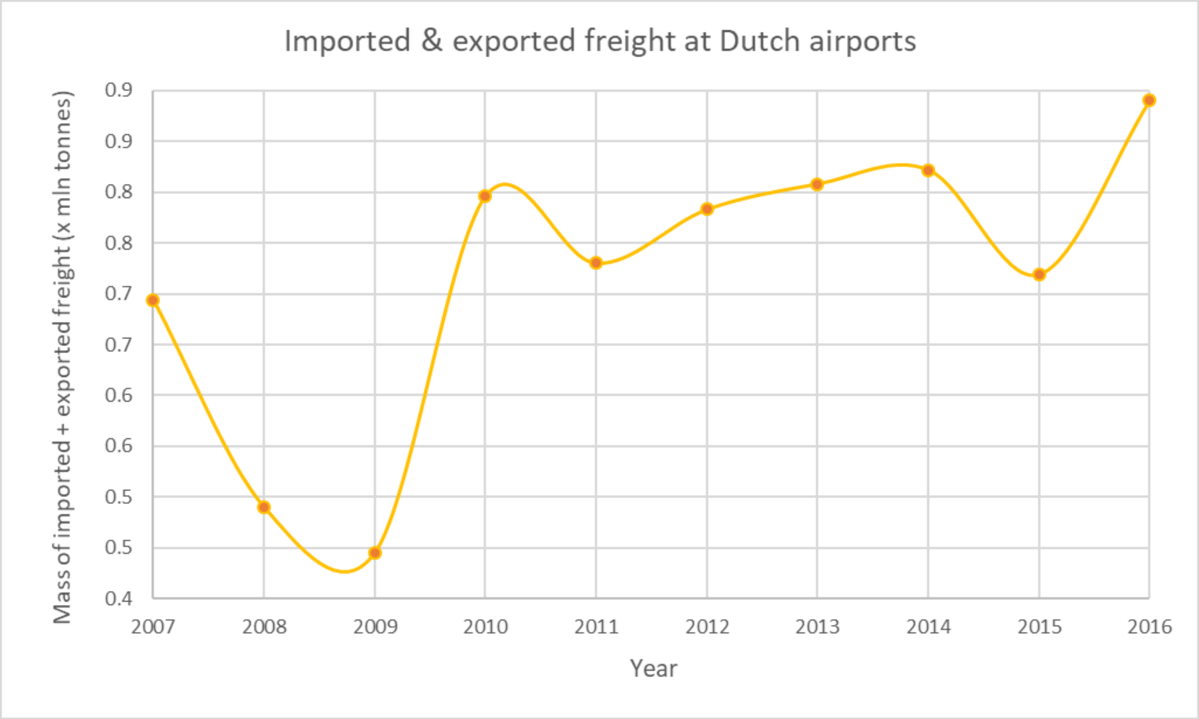

Figure 13: past mass of imported & exported freight at Dutch airports

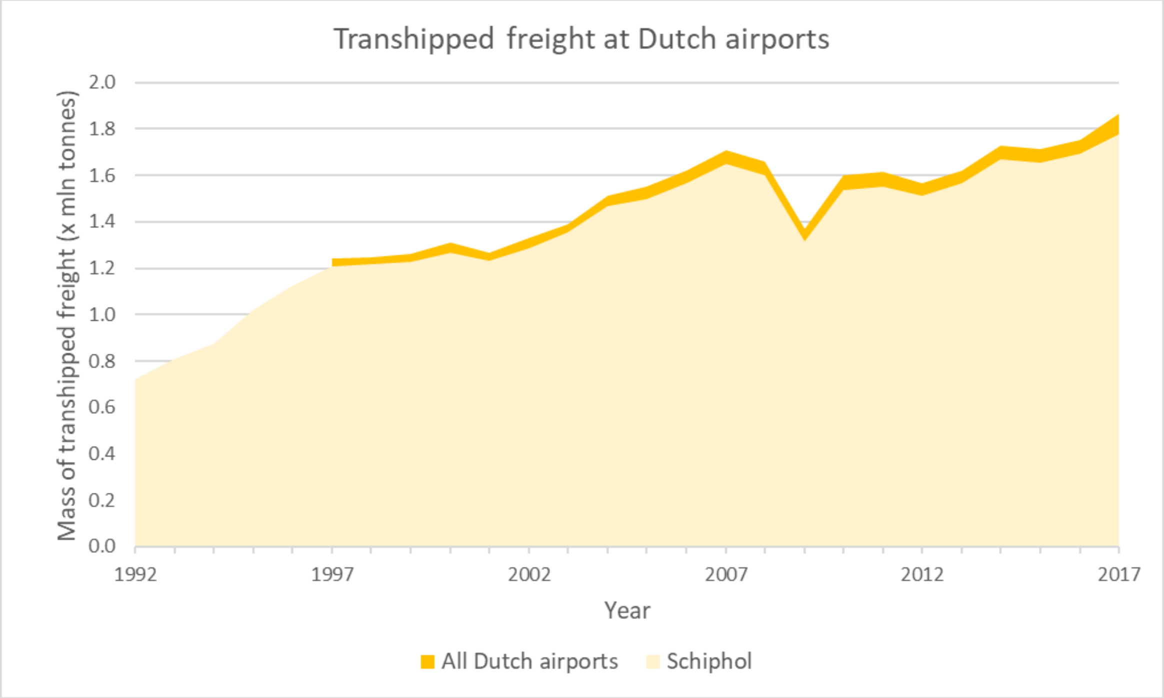

Figure 14: past mass of transhipped freight at Dutch airports. Statistics for all Dutch airports between 1992 – 1997 were not available and were therefore not included in the figure.

$M_{2016} = \mathbf{0.890}$ **million tonnes** (derived directly from CBS (2018c))

$$M_{1990} = M_{2007} \cdot \frac{T_{Schiphol,1992}}{T_{Schiphol,1997}}^{\left(\frac{1997-1990}{1997-1992}\right)} \cdot \frac{T_{all,1997}}{T_{all,2007}} = 0.694 \cdot \frac{0.724^{7/5}}{1.207} \cdot \frac{1.243}{1.710}$$

$= \mathbf{0.246}$ **million tonnes**

Using statistics from Schiphol (2016), it was assumed that 40% of freight (based on mass) was transported by passenger aircrafts while the remaining 60% of freight was transported by dedicated freighters. This share was assumed for both 1990 & 2016.

4.2. Past Dutch traffic demand

Jet fuel consumption is more closely related to the amount of traffic (in RPK for passenger transport or RTK for freight transport) than to the amount of passengers or mass of freight transported. Additionally, the demand growth projections used in this study (see section 4.3) apply to the amount of traffic instead of the amount of passengers or mass of freight transported. The aim of this section was therefore to determine the average distance travelled by aircrafts when transporting passengers or freight, so that the resulting amount of traffic could be calculated.

4.2.1. Past passenger traffic

To determine the average distance flown by passenger aircrafts, detailed statistics from CBS (2018d) were used. From 1998 – 2017, CBS (2018d) shows the amount of passengers on routes between Schiphol and one of 234 international '*partner airports*'. Per illustration, a selection of the statistics from CBS (2018d) is shown in table 5 below:

Table 5: section of the statistics from CBS (2018d).

Partner airport	**Year**	**Arrivals at Schiphol** (passengers / year)	**Departures from Schiphol** (passengers / year)
Argentinië, Buenos Aires	2016	60430	63168
Spanje, Fuerteventura	2016	51975	53649
Spanje, Girona	2016	42930	42368
Spanje, Gran Canaria	2016	173983	179014
…			

Using the coordinates of Schiphol Airport and each of the partner airports in CBS (2018d) the great circle distance (GCD) between Schiphol and each of the partner airports was calculated. The GCD is the shortest distance between two points on a globe. Because aircrafts will often not exactly follow the GCD and to account for additional distance flown during landing and lift-off, the actual flight distance was assumed to be slightly higher than the GCD. This was done following the same methodology as used by ICAO (2017a) which is discussed in section 4.4. If the GCD between Schiphol and a partner airport was less than 550 km, the flight distance was assumed to be the GCD + 50 km. If the GCD between Schiphol and a partner airport was more than 550 km but less than 5500 km, the flight distance was assumed to be the GCD + 100 km. And if the GCD between Schiphol and a partner airport was more than 5500 km, the flight distance was assumed to be the GCD + 125 km.

Using the arrivals and departures in 2016, the average distance flown per passenger at Schiphol from their last airport of departure or to their next airport of arrival was then calculated according to the formula below:

$$d_{p,year} = \frac{\sum_{route}\left((arrivals+departures)_{route,year} \cdot d_{p,route} \right)}{\sum_{route}(arrivals+departures)_{route,year}} = \mathbf{2903\ km} \text{ (in 2016)}$$

Since statistics for 1990 were not included in CBS (2018d) the average flight distance was also assumed to be 2903 km per arrival or departure in 1990. A calculation of the average flight distance for each year between 1998 – 2017 showed that the average flight distance deviated at most 10% from that in

2016 between 1998 - 2017. Thus, the assumption that the average flight distance in 1990 was equal to that in 2017 will not likely lead to a large uncertainty in the results.

Finally, the Dutch demand for passenger traffic in 1990 & 2016 was calculated as below. Note that only 50% of traffic associated with passenger arrivals and departures was allocated to the Netherlands, in accordance with the approach discussed in the methodology.

$$W_{p,1990} = 0.5 \cdot P_{all,1990} \cdot d_{p,2016,Schiphol} = 0.5 \cdot 15.81 \cdot 2903 \cdot 10^{-3} = \mathbf{22.94}\ \textbf{billion RPK}$$

$$W_{p,2016} = 0.5 \cdot P_{all,2016} \cdot d_{p,2016,Schiphol} = 0.5 \cdot 70.28 \cdot 2903 \cdot 10^{-3} = \mathbf{102.0}\ \textbf{billion RPK}$$

4.2.2. Past freight traffic

As was done for the average shipping distance in chapter 3, the average flight distance of freight transported by air was based on the estimation made by CBS (Chris de Blois, personal communication, June 1st, 2018). Based on the statistics published in CBS (2018c), CBS estimated the average flight distance of air freight to be 7648 km in 2016. This included the entire journey from first airport of departure and to last airport of arrival, so including any intermediate stops. Again, no estimation for 1990 could be made so the average flight distance in 1990 was assumed the same as in 2016. It was also assumed that the average flight distance of freight transported by passenger aircrafts did not deviate from that of freight transported by dedicated freighters.

The formulas below show how the Dutch demand for freight traffic in 1990 & 2016 was calculated. Note that only 50% of traffic associated with imports and exports at Dutch airports was allocated to the Netherlands, in accordance with the approach discussed in the methodology.

$$W_{f,1990} = 0.5 \cdot M_{1990} \cdot d_{f,2016,} = 0.5 \cdot 0.246 \cdot 7648 \cdot 10^{-3} = \mathbf{0.943}\ \textbf{billion RTK}$$

$$W_{f,2016} = 0.5 \cdot M_{2016} \cdot d_{f,2016,} = 0.5 \cdot 0.890 \cdot 7648 \cdot 10^{-3} = \mathbf{3.403}\ \textbf{billion RTK}$$

It was again assumed that 40% of freight traffic took place in passenger aircrafts while the remaining 60% took place in dedicated freighters.

4.3. Projected Dutch traffic demand

Two of the most detailed global air traffic forecasts available come from the two main aircraft manufacturers: Boeing (2017) and Airbus (2018a). In this study, only the forecast by Airbus was used since it is the most recently published and its results are more detailed than those from Boeing. Nonetheless, both studies show comparable results. Airbus (2018a) does not contain a forecast specific to the Netherlands, but a European forecast is included. The European air traffic growth rates presented by the study were therefore used and assumed representative for those of the Netherlands.

Airbus (2018a) used "*factors such as demographic and economic growth, tourism trends, oil prices and development of new and existing routes*" to forecast passenger & freight air traffic between different world regions (e.g. Europe – Pacific Asia) until 2037. Among the most important drivers for the outcome of the study were the expected growth in GDP (+1.8% per year in Europe) and trade (+2.8% per year in Europe). Globally, Airbus (2018a) expects a steady and continued increase of air traffic, albeit at lower growth rates than observed in the previous couple of years. Continued growth of passenger traffic can in part be attributed to a growing global middle class. Extra-European passenger traffic is projected to grow at a slightly higher rate than intra-European passenger traffic (due to relatively fast growth at hub airports in the Middle East), but overall the difference per region is small. It was therefore assumed that the average flight distance would not significantly change in the future.

Freight traffic is projected to increase at a somewhat slower rate than passenger traffic. This causes a higher share of future freight to be transported by passenger aircrafts than by dedicated freighters.

The forecasted annual growth rates of passenger and freight traffic in Europe between 2017 – 2037 are shown in the table below. No reliable forecast after 2037 could be found. It was therefore simply assumed that passenger and freight traffic after 2037 would increase at a rate that follows the trend forecasted by Airbus between 2017 - 2037. So for example, since passenger traffic was forecasted to grow by 3.5% per year between 2017 – 2027 and 3.3% per year between 2027 – 2037 (-0.2% compared to the previous decade), an annual growth rate of 3.1% (-0.2%) for 2037 – 2047 and 2.9% (-0.4%) for 2047 – 2057 was assumed.

Table 6: annual growth rates of passenger and freight traffic at Dutch airports used in this study.

Type of transport	**Annual growth**			
	2017–2027	**2027–2037**	**2037–2047**	**2047–2050**
Passenger traffic (RPK)	3.5%	3.3%	3.1%	2.9%
Freight traffic, in passenger aircrafts (RTK)	3.5%	3.3%	3.1%	2.9%
Freight traffic, in dedicated freighters (RTK)	3.3%	2.8%	2.3%	1.8%

Using the annual growth rates in table 6, the demand for passenger traffic in 2020, 2030 & 2050 was calculated as follows:

$$W_{p,2020} = W_{p,2016} \cdot \frac{P_{all,2017}}{P_{all,2016}} \cdot \left(1 + r_{p,2017-2027}\right)^3 = 102.0 \cdot \frac{76.20}{70.28} \cdot 1.035^3 = \mathbf{122.6}\ \textbf{million RPK}$$

$$W_{p,2030} = W_{p,2020} \cdot \left(1 + r_{p,2017-2027}\right)^7 \cdot \left(1 + r_{p,2027-2037}\right)^3$$
$$= iets \cdot 1.035^7 \cdot 1.033^3 = \mathbf{172.0}\ \textbf{million RPK}$$

$$W_{p,2050} = W_{p,2030} \cdot \left(1 + r_{p,2027-2037}\right)^7 \cdot \left(1 + r_{p,2037-2047}\right)^{10} \cdot \left(1 + r_{p,2047-2050}\right)^3$$
$$= 172.0 \cdot 1.033^7 \cdot 1.031^{10} \cdot 1.029^3 = \mathbf{319.1}\ \textbf{milllion RPK}$$

Likewise, the demand for freight traffic in 2020, 2030 & 2050 was calculated as below:

$$W_{fp,2020} = W_{f,2016} \cdot \%_{fp} \cdot \frac{T_{all,2017}}{T_{all,2016}} \cdot \left(1 + r_{fp,2017-2027}\right)^3 = 3.403 \cdot 40.1\% \cdot 1.0628 \cdot 1.035^3$$
$$= \mathbf{1.61}\ \textbf{million RTK}$$

$$W_{fp,2030} = W_{fp,2020} \cdot \left(1 + r_{fp,2017-2027}\right)^7 \cdot \left(1 + r_{fp,2027-2030}\right)^3 = 1.61 \cdot 1.035^7 \cdot 1.033^3$$
$$= \mathbf{2.26}\ \textbf{million RTK}$$

$$W_{fp,2050} = W_{fp,2030} \cdot \left(1 + r_{fp,2027-2037}\right)^7 \cdot \left(1 + r_{fp,2037-2047}\right)^{10} \cdot \left(1 + r_{fp,2047-2050}\right)^3$$
$$= 2.26 \cdot 1.033^7 \cdot 1.031^{10} \cdot 1.029^3 = \mathbf{4.19}\ \textbf{million RTK}$$

$$W_{ff,2020} = W_{f,2016} \cdot \%_{ff} \cdot \frac{T_{all,2017}}{T_{all,2016}} \cdot \left(1 + r_{ff,2017-2027}\right)^3 = 3.403 \cdot 59.9\% \cdot 1.0628 \cdot 1.033^3$$
$$= \mathbf{2.39}\ \textbf{million RTK}$$

$$W_{ff,2030} = W_{ff,2020} \cdot \left(1 + r_{ff,2017-2027}\right)^7 \cdot \left(1 + r_{ff,2027-2030}\right)^3 = 2.39 \cdot 1.033^7 \cdot 1.028^3$$
$$= \mathbf{3.26}\ \textbf{million RTK}$$

$$W_{ff,2050} = W_{ff,2030} \cdot \left(1 + r_{ff,2027-2037}\right)^7 \cdot \left(1 + r_{ff,2037-2047}\right)^{10} \cdot \left(1 + r_{ff,2047-2050}\right)^3$$
$$= 3.26 \cdot 1.028^7 \cdot 1.023^{10} \cdot 1.018^3 = \mathbf{5.23}\ \textbf{million RTK}$$

4.4. Specific fuel consumption

4.4.1. Specific fuel consumption of passenger traffic in 2015

Calculating the fuel consumption of passenger traffic is complicated by the fact that for a specific route, fuel consumption per RPK depends greatly on the flight distance of that route. For various reasons, long-haul flights normally have far lower fuel consumption per RPK than short-haul flights. To account for the dependency of specific jet fuel consumption on flight distance, as well as some other factors that differ per route, this research made use of the 2017 version of the ICAO carbon offsetting calculator (ICAO, 2017a; 2018). Route-specific data for flights between Schiphol and 268 partner airports were derived from this calculator and combined with the statistics from CBS (2018d) describing the amount of passengers per route. This section first discusses the methodology used by the ICAO carbon offsetting calculator after which the average specific fuel consumption (per RPK) of all flights at Schiphol is calculated.

The ICAO carbon offsetting calculator is a peer-reviewed calculator (ICAO, 2016b) that allows the user to calculate the fuel consumption and CO_2 emissions per person on a flight between two international airports. The calculator first estimates the flight distance between the airports, using the GCD between the airports plus a correction factor (50 km for GCD < 550 km, +100 km for 550 km > GCD < 5500 km and +125 km for GCD > 5500 km). Next, a database of scheduled flights is used to determine which types of aircrafts operate most on the route between the airports. The fuel burn of these aircraft types is then used to find the weighted average fuel consumption of a flight on the route. The fuel burn per aircraft type is based on information provided by the manufacturers and was corrected with actual in-use fuel consumption data from airlines.

Since passenger aircrafts often simultaneously transport passengers and freight only a portion of their fuel consumption is allocated to passenger transport. This allocation is done on the basis of mass assuming a mass of 150 kg per person (including its luggage and required infrastructure such as seating, crew & toilets). The amount of passenger seats in the aircraft is estimated using a standard cabin layout while the percentage of seats occupied is determined using operational data.

The methodology behind the ICAO carbon offsetting calculator (including formulas) is described in more detail in ICAO (2017a). The data for version 10 of the calculator (which was used for this study) was valid for 2015. Per illustration, a selection of the data retrieved from the calculator is shown in table 7 below. Figure 15 shows the fuel consumption per person on each of the 268 routes between Schiphol and a partner airport for which results were available. The decreasing slope of the trendline shows how fuel consumption per RPK decreases with flight distance.

Table 7: illustration of the data derived from the ICAO calculator for 4 of the 268 unique routes. The jet fuel consumption (last column) was calculated by dividing the CO_2 emissions by 3.16 (consistent with the ICAO methodology). The abbreviations shown in the first 3 columns are the IATA codes for the corresponding airports or aircrafts.

Origin	Destination	Most occurring aircraft types	Journey distance (km)	CO_2 Emissions (kg pp per journey)	Jet fuel consumption (kg pp per journey)
AMS	AAL	E75, E90	623	109.3	34.6
AMS	ABZ	73H, 73W, E75, E90	702	103.9	32.9
AMS	ACC	772, 77W	5209	348.4	110.3
AMS	ACE	73H	3003	223.7	70.8

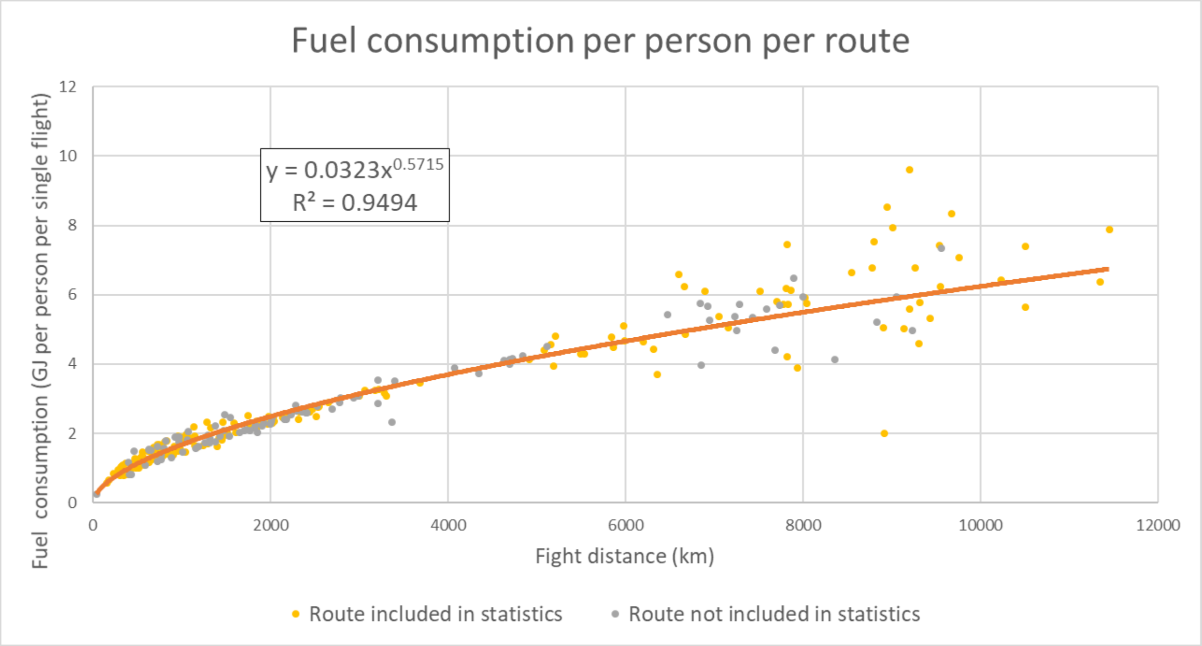

Figure 15: fuel consumption per person in a flight on one of 268 routes between Schiphol and international partner airports included in the ICAO carbon offsetting calculator. The trendline and formula show the relationship between fuel consumption (per single flight) and flight distance.

Most of the 179 routes for which CBS (2018d) recorded passenger volumes in 2015 were included in the results from the ICAO calculator. On these routes, the jet fuel consumption per passenger was multiplied with the amount of passengers to find the total 2015 fuel consumption on that route. On the few routes which were included in CBS (2018d) but for which no fuel consumption data was available the formula corresponding to the trendline in figure 15 was used instead (where *x* is the flight distance). Finally, the total 2015 fuel consumption on all routes was summed up and divided by the total passenger transport on these routes to find the average 2015 fuel consumption of passenger traffic at Schiphol:

$$fc_{p,average,2015} = \sum_{route} \left(P_{route,2015} \cdot fc_{p,route,2015}\right) \Big/ \sum_{route} \left(P_{route,2015} \cdot d_{route}\right)$$

$$= 149\ PJ\ /\ 164\ bln\ RPK = \mathbf{0.909\ MJ\ /\ RPK}$$

4.4.2. Specific fuel consumption of freight traffic in 2015

Air freight transport exists in two forms: freight transport in the belly of passenger aircrafts, and freight transport in dedicated freighter aircrafts. The specific fuel consumption of freight traffic in passenger aircrafts was directly derived from the specific fuel consumption of passenger traffic (as calculated in section 4.4.1.). Following the assumption by the ICAO that 1 passenger is responsible for 150 kg of mass (ICAO, 2017a) in a passenger aircraft, the specific fuel consumption of freight traffic in passenger aircrafts was calculated as follows:

$$FC_{fp,2015} = FC_{p,average,2015} \cdot \frac{RTK}{RPK} = 0.909 \cdot \frac{1}{0.150} = \mathbf{6.06\ MJ\ /\ RTK}$$

To calculate the fuel consumption of freight traffic in dedicated freighters a different method was used, based on the European environment agencies *aviation emissions calculator* (EEA, 2017b). This calculator calculates the fuel burn of an aircraft when given the aircraft type and flight distance. The data behind the calculator is valid for 2015.

To be able to use the EEA's aviation emissions calculator it thus had to be determined which types of freighters operated at Schiphol and what their average flight distance was. The amount of movements per freighter type at Schiphol were simply retrieved from Schiphol (2016). The average flight distance of each aircraft type instead had to be estimated. This was done as described below:

From aircraft manufacturers manuals, the maximum mass of freight transported per flight (the maximum structural revenue payload) and the flight distance at which the aircraft was designed to be operated (the design range at maximum revenue payload) were retrieved from aircraft manufacturer manuals (aerospace-technology.com, 2018; BAE systems, 2004; Airbus, 2018b; Boeing, 2018; DHL, 2018; Safair, 2018). This information was used to calculate the total mass of freight that would have been transported in 2016 if each freighter operated at its maximum structural revenue payload. By comparing this value to the actual mass of freight transported by freighters in 2016 (from Schiphol, 2016), it was determined that freighters operated on average at 56.4% of their maximum structural revenue payload. This percentage was assumed to apply equally to each aircraft type. Then, using the percentage of maximum payload transported and amount of movements per aircraft type, it was determined how much traffic (in RTK) would have been caused by freighters if their flight distance equalled their design range. By comparing this value to the actual amount of freight traffic estimated by CBS (Chris de Blois, personal communication, June 1st, 2018) it was determined that on average, each aircrafts flight distance had been 102.6% of its design range. Finally, this distance was used as an input to the EEA's aviation emissions calculator to find the fuel burn of each flight.

The data used in the calculation can be found in appendix B. The results of the calculation are shown in table 8 below. The specific fuel consumption of freight traffic by dedicated freighters in 2015 was calculated to be **6.54 MJ / RTK**.

Table 8: calculated specific jet fuel consumption of freight traffic by freighters operating at Schiphol.

Freighter type	**Amount of movements in 2016**	**Assumed payload** (tonnes of freight per movement)	**Specific fuel consumption** (MJ jet fuel per RTK)
Boeing 777-200	6249	57.50	5.32
Boeing 747-400	5951	63.69	7.53
Boeing 747-8	2306	77.62	6.65
Airbus A300	1248	27.11	10.3
Boeing 757-200	534	18.46	10.5
Embraer EMB 120	396	1.87	20.0
MD11	289	48.77	8.93
Boeing 737-400	274	9.63	15.8
Airbus A330-200	202	36.64	7.79
Boeing 737-300	132	11.12	12.7
Airbus A330-300	78	33.82	8.00
Boeing 747-200	56	62.08	8.50
Boeing 767-300	54	29.58	8.35
Airbus A310	34	21.98	10.1
Bae 146/AVRO RJ	2	5.35	24.6
		Weighted average	6.54

4.4.3. Past & projected efficiency improvements

The specific fuel consumption of passenger and freight traffic in 2015 from section 4.4.1 & 4.4.2 was combined with measured and projected fuel efficiency improvements to estimate the specific fuel consumption of passenger and freight traffic in 1990, 2016, 2030 & 2050. It is important to differentiate here between fuel efficiency improvements of aircrafts that are yet to be built and fuel efficiency improvements of in-use aircrafts. For this study it was assumed that the in-use fuel efficiency improvements would lag behind the fuel efficiency improvements of yet to be built aircrafts by the mean aircraft age. Over the last decade, the mean aircraft age has been relatively stable around 10 years for passenger aircrafts and around 19 years for dedicated freighters (EEA, 2017a). The higher mean aircraft age of dedicated freighters is because a large portion of the dedicated freighter fleet consists of converted out-of-service passenger aircrafts (Airbus, 2018a). Efficiency improvements made in newly built aircrafts will therefore take longer to have an effect on the fuel efficiency of the dedicated freighter fleet.

Past fuel efficiency improvements of newly built aircrafts between 1960 – 2014 were analysed by the international council on clean transportation (Kharina & Rutherford, 2015) and shown in figure 16. This data was used to determine the short term in-use fuel efficiency improvements (between 2015 – 2024 for passenger aircrafts and between 2015 – 2033 for freighters) as well as the past fuel efficiency improvements (between 1990 – 2015 for both passenger aircrafts and freighters). For example: the fuel efficiency of newly built aircrafts increased by 1.1% per year between 2010 – 2014. It was thus assumed that the in-use fuel efficiency of passenger aircrafts increased by 1.1% between 2020 – 2024 and that the in-used fuel efficiency of dedicated freighters increased by 1.1% between 2029 – 2033.

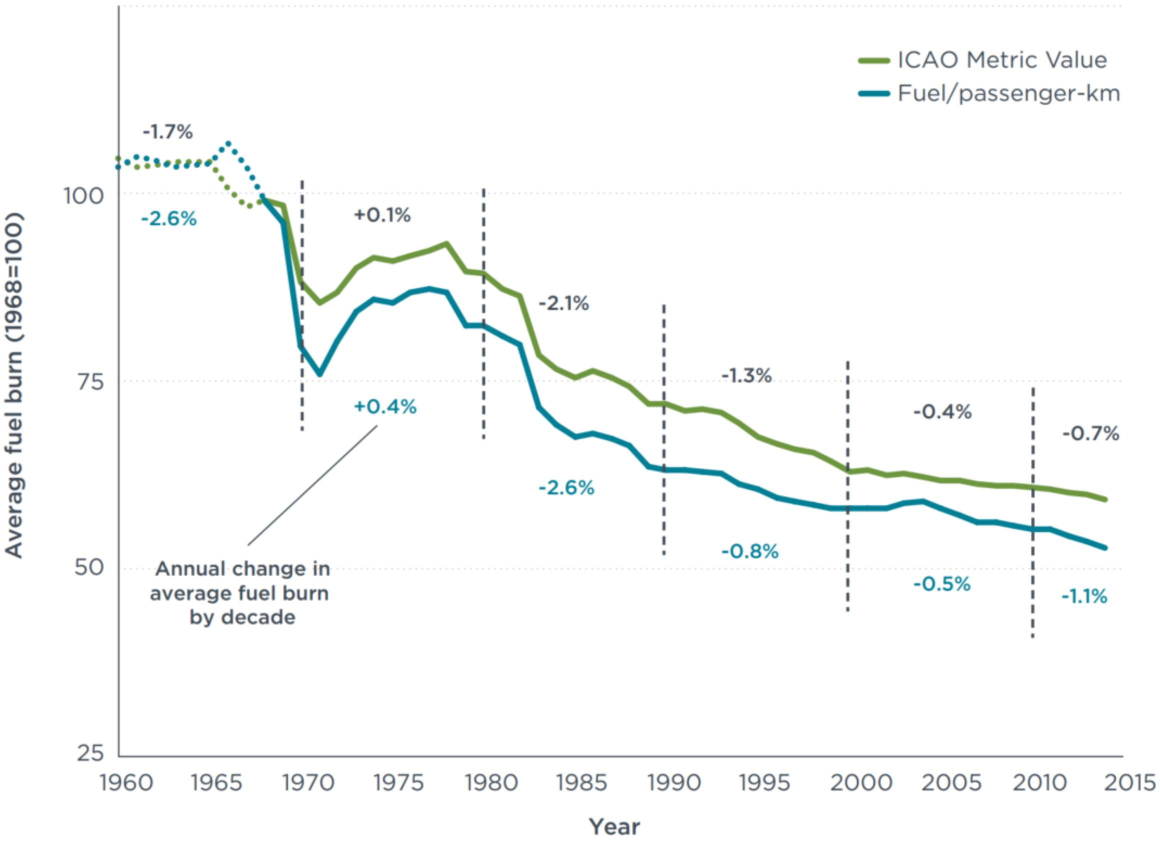

Figure 16: past efficiency improvements in new aircrafts, from Kharina & Rutherford (2015).

In 2017, the ICAO adopted the Aeroplane CO_2 Emissions Certification standard, which aims to increase the fuel efficiency of newly built aircrafts with 2% per year. The standard will come into effect for new aircraft type designs starting 2020 and for already in-production aircraft designs starting 2023. In-production aircrafts which do not meet the standard by 2028 will no longer be allowed to be produced (ICAO, 2016; ICAO, 2017b). For this study it was assumed that the ICAO's CO_2 standard would indeed lead to a 2% fuel efficiency improvement in newly built aircrafts, starting 2023. However, given the time lag between newly built and in-use fuel efficiency improvements, this 2% annual improvement would only come into effect starting 2033 for passenger aircrafts and starting 2042 for dedicated freighters.

For the period 2024 – 2033 for passenger aircrafts and the period 2033 – 2042 for freighters neither the past efficiency improvements from Kharina & Rutherford (2015) or the projected efficiency improvements resulting from the ICAO CO_2 emissions standard could be used. It was therefore simply assumed that fuel efficiency would increase at the same rate as in 2010 – 2014 for newly built aircrafts, thus at 1.1% per year.

Appendix B shows which annual efficiency improvement was used for each year to calculate the specific fuel consumption of passenger & freight traffic in 1990, 2016, 2030 & 2050. The results of the calculation are shown in table 9.

Table 9: specific fuel consumption of passenger and freight traffic assumed in this research.

Specific fuel consumption	**1990**	**2016**	**2020**	**2030**	**2050**
MJ per RPK	1.28	0.90	0.88	0.78	0.53
MJ per RTK, in passenger aircrafts	8.53	6.03	5.84	5.23	3.56
MJ per RTK, in dedicated freighters	8.72	6.54	6.32	5.94	4.39

4.5. Final Dutch jet fuel demand

The jet fuel demand that is allocated to the Netherlands (the Dutch demand) can now be calculated as by combining the traffic demand with the specific fuel consumption:

$$E_{year} = W_{p,year} \cdot fc_{p,year} + W_{fp,year} \cdot fc_{fp,year} + W_{ff,year} \cdot fc_{ff,year}$$

$$E_{1990} = 22.94 \cdot 1.28 + 0.38 \cdot 8.53 + 0.56 \cdot 8.72 = \mathbf{37.5\ PJ}$$

$$E_{2016} = 102.0 \cdot 0.90 + 1.36 \cdot 6.03 + 2.04 \cdot 6.54 = \mathbf{113.8\ PJ}$$

$$E_{2020} = 122.6 \cdot 0.88 + 1.61 \cdot 5.84 + 2.39 \cdot 6.32 = \mathbf{132.0\ PJ}$$

$$E_{2030} = 172.0 \cdot 0.78 + 2.26 \cdot 5.23 + 3.26 \cdot 5.94 = \mathbf{166.1\ PJ}$$

$$E_{2050} = 319.1 \cdot 0.53 + 4.19 \cdot 3.56 + 5.23 \cdot 4.39 = \mathbf{208.1\ PJ}$$

These results are also shown in figure 17. Unlike the demand for marine fuels, the demand for jet fuels is not expected to peak before 2050. This is primarily because demand growth projections for international aviation are higher than those for international shipping, even though the projected growth rates are much lower than what has previously been observed in the Netherlands. Furthermore it can be concluded that both in the future and in the past, the majority of the Dutch jet fuel demand originates from passenger traffic.

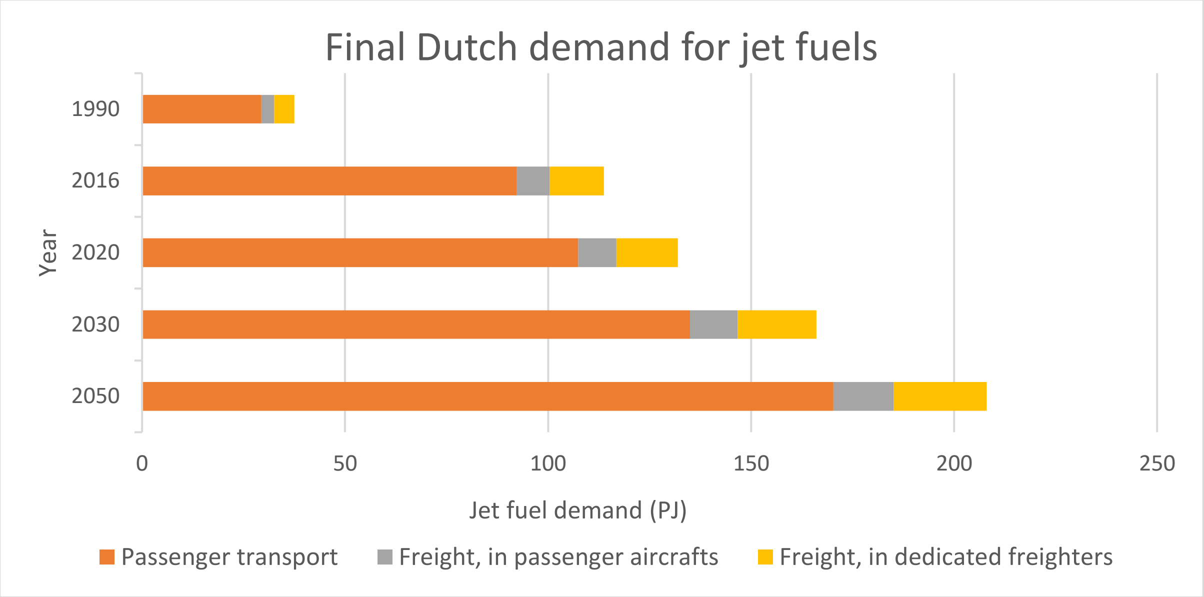

Figure 17: jet fuel demand allocated to the Netherlands. The projected demand for 2030 & 2050 have been added to the OPERA model.

5. Other model inputs

Besides the addition of a demand for marine and jet fuels several other components of OPERA also had to be adjusted. First, options were added that represent the production of marine fuels and jet fuels via both fossil and renewable conversion pathways. These options are described in the first two sections of this chapter. Second, constraints on the maximum allowable GHG emissions in 2030 and 2050 were added in line with the requirements of each sub-question. An overview of these constrains is given in section 5.3. Next, section 5.4 discusses which amount of biomass was assumed available in 2030 and 2050. Finally, section 5.5 shows the assumed prices of energy carriers.

5.1. Fossil fuel refining

OPERA already contained an option that represents the conversion of crude oil into petroleum products based on a detailed analysis with the refinery model SERUM (Stienstra, 2006). Table 10 shows the projected energy balance of this option in 2030 and 2050. HFO and jet fuel were left out of the energy balance given that the emissions associated with their consumption are normally not counted towards the national emissions. For this research on the contrary, the refining of crude oil into HFO and jet fuel did have to be included. This was done through the addition of two new options: one representing the refining of crude oil into HFO and one representing the refining of crude oil into jet fuel.

Table 10: energy balance of the fossil oil refinery option that was already present in OPERA.

Year	Incoming energy carriers				Outgoing energy carriers				
	Crude oil	Natural gas	Electricity	Heat	Petroleum products				Residual gasses
					Diesel	Gasoline	LPG	Other	
2030	1	0.0108	0.0066	0.0678	0.4896	0.3258	0.0373	0.0950	0.0569
2050	1	0.0129	0.0062	0.0625	0.4866	0.3382	0.0387	0.0956	0.0484

Table 11 shows the data that was added alongside the two new refinery options which consists of the their energy balances and costs. The energy balances of the two new options were based on that of the already existing refinery option (table 10). This was done by assuming that the same amount of energy carriers required for the production of one unit of petroleum products was also required for the production of one unit of HFO or jet fuel. The total costs of the two options (which includes capital costs, operational costs and energy costs) were based on the price of crude oil in OPERA. To reflect the higher market value of jet fuel compared to HFO, the costs of jet fuel refining were set at 130% of the crude oil price while the costs of HFO refining were set at 78% of the crude oil price. The refining of crude oil into jet fuel was thereby made more costly than the refining of crude oil into HFO, creating a larger financial incentive to replace fossil jet fuel with renewable alternatives.

As with most options in OPERA, the GHG emissions associated with the refining of crude oil into HFO and jet fuel were calculated by subtracting the carbon content of the outgoing energy flows from that of the incoming energy flows. Given the large efficiency of the refining process, however, these emissions were negligible compared to the combustion emissions of HFO and fossil jet fuel.

Table 11: energy balance and costs associated with the two added options representing the conversion of crude oil into HFO or jet fuel..

Incoming energy carriers	**2030**	**2050**
Crude oil	1.0552	1.0426
Heat	0.0715	0.0651
Natural gas	0.0114	0.0134
Electricity	0.0069	0.0064
Outgoing energy carriers	**2030**	**2050**
HFO or jet fuel	1.0000	1.0000
Residual gasses	0.0601	0.0505
Costs (€ / GJ HFO or kerosene)	**2030**	**2050**
HFO refining	10.55	11.20
Jet fuel refining	17.65	18.74

5.2. Biofuel refining

Six options were added to OPERA which represent the conversion of biomass into biofuels via different conversion pathways. These are:

1. The conversion of lignocellulosic biomass into drop-in fuels replacing diesel and jet fuels via *Fischer-Tropsch*;
2. The conversion of lignocellulosic biomass into drop-in fuels replacing gasoline, diesel, marine fuels and jet fuels via *pyrolysis* with *hydrogen upgrading*;
3. The conversion of lignocellulosic biomass into drop-in fuels replacing gasoline, diesel, marine fuels and jet fuels via *hydrothermal liquefaction* (HTL) with *hydrogen upgrading*;
4. The *hydroprocessing* (HEFA) of used cooking oil (UCO) into drop-in fuels replacing jet fuels, diesel and LPG;
5. The conversion of lignocellulosic biomass into drop-in fuels replacing ethanol via *fermentation*;
6. The conversion of ethanol into drop-in fuels replacing jet fuels, gasoline and diesel via *alcohol-to-jet* (AtJ) technology.

The energy balance and costs of these options are shown in figure 18 and 19. In all cases, the data was directly taken from or based on de Jong (2015, 2018). De Jong calculated the costs using an *nth plant analysis* in which the future cost of a conversion pathway are based on that of the pioneer plant and an assumed learning rate. Since the original study only applied this methodology to calculate the costs in 2030, the cost in 2050 had to be calculated by extending this methodology.

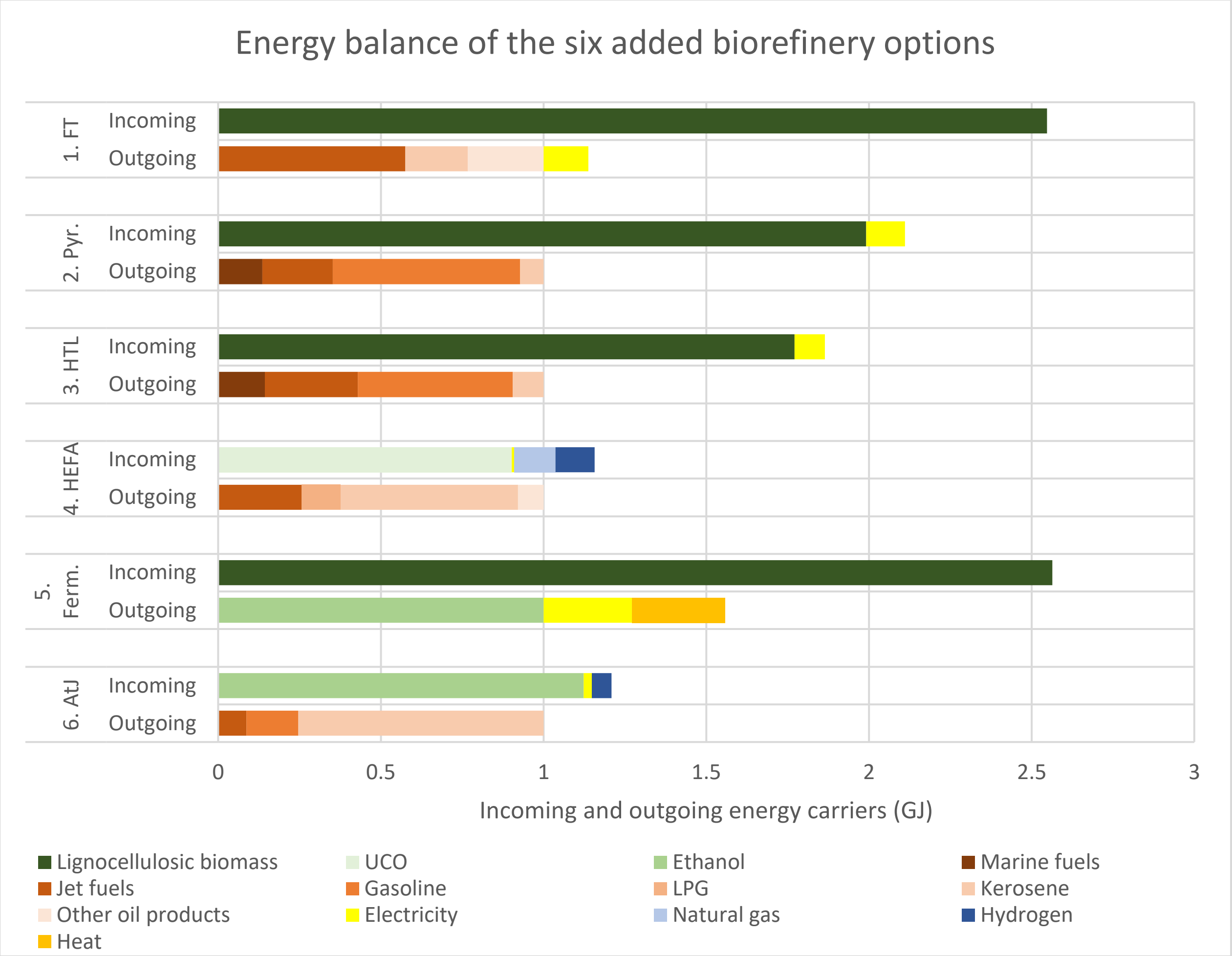

Figure 18: energy balance of the six added biorefinery options. The fuels depicted in the graph represent drop-in fuels replacing that particular kind of fossil fuel.

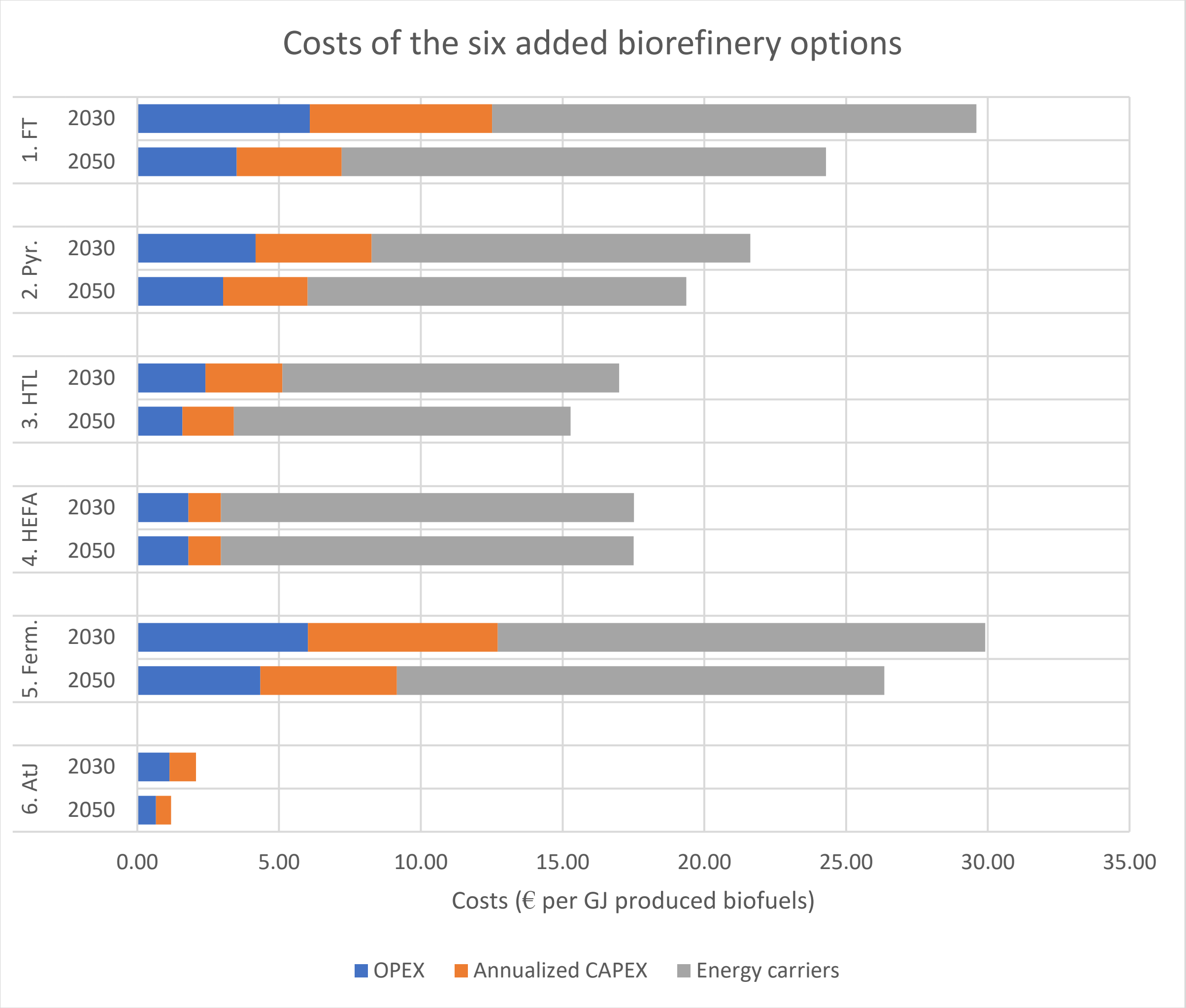

Figure 19: costs per GJ produced biofuels (marine fuels, diesel, gasoline, LPG, jet fuels, ethanol & other oil products) of the six added biorefinery options. The annualized CAPEX were calculated using a lifetime of 20 years and 8000 load hours per year. The cost of energy carriers include only the cost of energy carriers that have to be 'bought' by OPERA. These are lignocellulosic biomass, UCO and natural gas. The costs of other energy carriers such as ethanol or electricity are not included in this price (hence the low costs of AtJ).

Besides the six added options based on de Jong (2015, 2018), OPERA already contained a large amount of other options representing the conversion of biomass into biofuels. However, none of these options included marine or jet fuels as outputs. The conversion pathways represented in the options already contained in OPERA are:

1. The conversion of lignocellulosic biomass into drop-in fuels replacing diesel and other oil products via Fischer-Tropsch, including a variant with carbon capture and storage (CCS);
2. The conversion of lignocellulosic biomass into drop-in fuels replacing diesel via the production of dimethylether (DME);
3. The conversion of lignocellulosic biomass into drop-in fuels replacing gasoline via the production of methanol;
4. The conversion of various kinds of biomass (including lignocellulosic biomass) into substitute natural gas (SNG) via gasification;
5. The conversion of lignocellulosic biomass, starch or sugars into biogas and drop-in fuels replacing ethanol or hydrogen via fermentation or anaerobic digestion.

Furthermore, several power-to-liquid options derived from (Schmidt et al., 2016a, 2016b, 2018) were present in OPERAs database which convert electricity into liquid hydrocarbon fuels (drop-in fuels replacing jet fuel, gasoline, diesel, LPG and other oil products) via hydrogen or methanol from electrolysis and CO_2. These options are generally expensive, but often the only option capable of producing renewable fuels without consuming biomass. Given that power-to-liquid technology is still in an early stage of development it was assumed to be available only in 2050.

The current way in which the biorefinery options were entered into OPERA has one major drawback in that the biofuels are produced in a fixed ratio to each other. The Pyrolysis pathway for example always produces 58% drop-in gasoline, 22% drop-in diesel, 14% drop-in marine fuel and 7% drop-in jet fuels. In reality however there is some flexibility in the ratio in which the biofuels can be produced. Additionally there is some flexibility on the demand side as well (ships for example could also burn diesel instead of marine fuels) and fuels that are produced in excess could be sold abroad. To implement this flexibility into OPERA and to prevent that the model is not able to find a solution if one kind of biofuel is overproduced, some kinds of biofuels were allowed to be converted into other kinds of biofuels. Specifically, biobased drop-in fuels replacing diesel, ethanol, gasoline and jet fuels were all allowed to be converted into drop-in fuels replacing marine fuels and drop-in fuels replacing jet fuels were allowed to be converted into drop-in fuels replacing diesel. The effect of this is discussed in the discussion.

5.3. Maximum allowable GHG emissions

The GHG emission reduction targets for each sub question were calculated in accordance with the methodology described in section 2.5. An overview of these targets is shown in table 13.

In sub-question 4, specific targets for the emissions from international shipping and aviation exist. For international shipping, the 2050 target is set at 50% of the business-as-usual combustion emissions in 2008. Using an emission factor of 0.0774 Mt CO_2-eq / PJ marine fuels (based on Zijlema, 2017), the maximum allowed GHG emissions from international shipping in 2050 were calculated as follows:

$$E_{marine,2008} \cdot EF_{marine} \cdot 50\% = 129.9 \cdot 0.0774 \cdot 0.5 = 4.83 \text{ Mt CO}_2\text{-eq}$$

To calculate the 2030 emission target the 2020 business-as-usual emissions first had to be calculated. These are $E_{marine,2020} \cdot EF_{marine} = 173.7 \cdot 0.0744 = 12.92$ Mt CO_2-eq. The 2030 emission target was now determined by the requirement that GHG emissions from international shipping would decrease linearly between 2020 & 2050. As such, the 2030 emission target for international shipping was set at:

$$12.92 - (12.92 - 4.83) \cdot \frac{2030-2020}{2050-2020} = 10.22 \text{ Mt CO}_2\text{-eq}$$

For international aviation, the maximum allowed GHG emissions in both 2030 & 2050 were set at the business-as-usual emissions in 2020. These are $E_{jet,2020} * EF_{jet} = 132.0 \cdot 0.0715 = 9.44$ Mt CO_2-eq. The emission factor of jet fuels was again based on Zijlema (2017).

Table 12 shows the emissions from international shipping and aviation that would occur in a business-as-usual scenario given the marine and jet fuel demand from chapter 3 & 4. It shows that compliance with the sector-specific GHG emission restrictions set out in sub-question 4 requires significant emission reductions to occur in the sectors. In OPERA, this means that a large amount of HFO & fossil jet fuel will have to be substituted with biobased alternatives.

Table 12: comparison of business-as-usual emissions and emission target in sub-question 4.

	2030	2050
Marine fuel demand (PJ)	177.9	155.4
GHG emissions in business-as-usual scenario (Mt CO_2-eq)	13.77	12.03
Required emission reduction in reference to business-as-usual scenario (Mt CO_2-eq)	3.13	7.00
Jet fuel demand (PJ)	166.1	208.1
GHG emissions in business-as-usual scenario (Mt CO_2-eq)	11.87	14.88
Required emission reduction in reference to business-as-usual scenario (Mt CO_2-eq)	2.44	5.44

In sub-question 5 the inclusion of bunker fuel emissions in the national total increased the 1990 reference emissions by:

$E_{marine,1990} \cdot EF_{marine} + E_{jet,1990} \cdot EF_{jet} ==$ 9.45 Mt CO_2-eq.

The additional emissions in the reference year meant that 9.45 · 51% = 4.82 Mt extra emissions in 2030 and 9.45 · 5% = 0.47 Mt extra emissions in 2050 were allowed.

Table 13: maximum allowed GHG emissions in 2030 and 2050 for the three policy scenarios described in sub-question 3, 4 & 5.

Sub-question	Emissions from international shipping and aviation included in national target	Maximum allowed GHG emissions (Mt CO_2-eq)		
		Target applies to	2030	2050
Q3	Not included	National total	114.21	11.20
		International shipping	no separate target	no separate target
		International aviation		
Q4	Not included	National total	114.21	11.20
		Marine fuel emissions	10.64	5.03
		Jet fuel emissions	9.43	9.43
Q5	Included	National total	119.03	11.67
		Marine fuel emissions	no separate target	no separate target
		Jet fuel emissions		

5.4. Biomass availability

Dutch biomass consumption has grown rapidly over the past 15 years (CBS, 2018g) following policy efforts to establish a biobased economy in the country. With key applications in the area of renewable electricity, fuel and chemical production the biomass consumption in the Netherlands can be expected to increase further into the future (Langeveld et al., 2016). The increasing demand for biomass feedstocks makes the availability of domestic and imported biomass an essential factor that determines the scenario projections in this study. It is however highly uncertain how much biomass will be available to the Netherlands in 2030 and beyond to 2050. To capture this uncertainty the main results of this research have been calculated for three biomass availability scenarios (low, medium & high). Table 14 shows which potentials were assumed in all three scenarios. In the remainder of this section the assumed potentials are substantiated by a discussion of the factors that influence them.

5.4.1. Domestic supply of biomass

OPERA distinguishes between domestically supplied and imported biomass. The potential of domestically supplied biomass is well understood in the Netherlands and OPERA already contained detailed estimates about this potential. This biomass supply potential was based on multiple studies (Elbersen et al., 2016; Ros et al., 2011; Ruiz et al., 2015; Schoots et al., 2016) and is shown in figure 20. Figure 20 shows that the domestic biomass potential is relatively low and exists of many types of biomass. Depending on the desired application, some of these biomass types are more suitable than others. For example, while lignocellulosic biomass can be used to produce most types of biofuels through a variety of production pathways, manure and other wet waste streams can often only be used to produce biogas through anaerobic digestion. Because of its relatively low potential and the fact that the biomass potential in the Netherlands is well understood the domestically available biomass was assumed equal in all three scenarios.

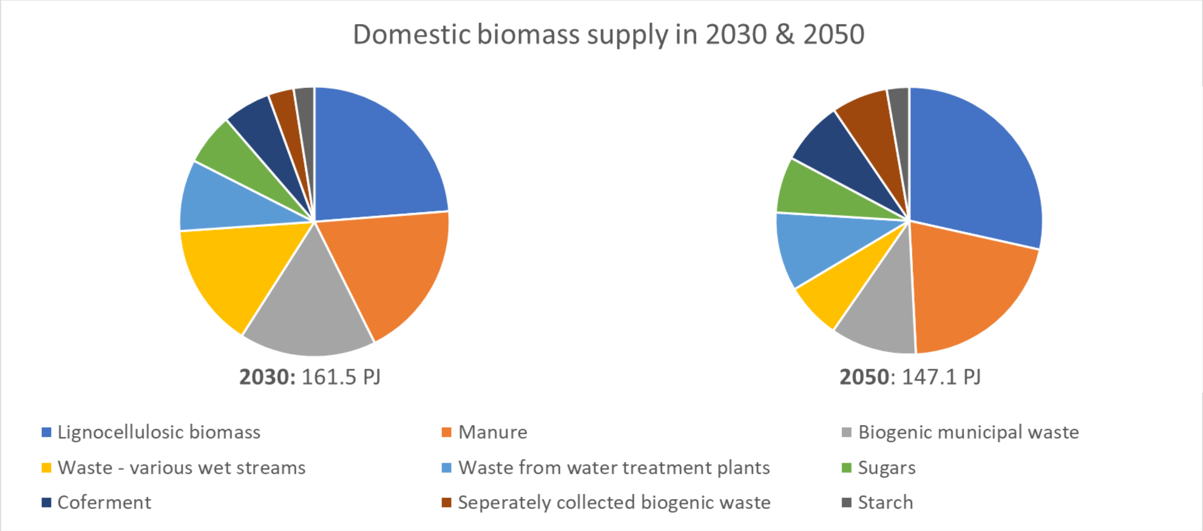

Figure 20: availability of domestically supplied biomass in 2030 & 2050 as assumed in OPERA. Equal availability was assumed for all three scenarios. Biogenic municipal waste refers to biogenic waste that is mixed with non-biogenic waste. Separately collected biogenic waste refers to separately collected biogenic waste from residents and the food industry.

5.4.2. Intra-EU and extra-EU imports of biomass

The potential of imported biomass is much higher than that of domestically supplied biomass but relies on many factors and their future developments (Ros et al., 2011). First, the import potential depends on the global biomass supply available for energy purposes. The global supply available for energy purposes in turn depends heavily on competition with agriculture and forestry over land. Increased agricultural efficiency and a shift to a less meat-based diet would increase the future amount of land that is available to grow biomass on. On the other hand, population increase and soil degradation would decrease it (Dornburg et al., 2010). Creutzig et al. (2015) show the large disagreement among studies projecting the global sustainable biomass supply in 2050, with estimations varying anywhere between 100 – 900 EJ. Ros et al. (2011) are on the conservative side of this range, concluding that a global sustainable supply of 150 EJ is realistic while 400 EJ could be achieved only if far-reaching technological and institutional developments take place. Regardless the global biomass supply, not all produced biomass will be available for trade. This is because a large portion of biomass may be consumed domestically by the country in which it is produced. Also, not all kinds of biomass are suitable to be transported over great distances and the required infrastructure is not always available. Finally, the Netherlands will have to compete with other countries over the available tradable biomass. With ambitious global GHG reduction targets, biomass may become a highly wanted resource for multiple countries and competition may be fierce.

To give a possible range of import potentials, Ros et al. (2011) calculated the amount of biomass that would be available to the Netherlands if the global tradable supply was equally distributed per capita (0.19% for the Netherlands) or per unit gross national product (0.49% for the Netherlands). Assuming that at most 50% of the global supply would become available for trade, this would mean that the maximum Dutch import potential by 2050 would be 142.5 – 367.5 PJ if global supply reached 150 EJ by 2050. If global supply reaches 400 EJ, the import potential to the Netherlands would be 380 – 980 PJ.

The assumed range of biomass import potentials for this research follows the estimates by Ros et al. (2011) but takes into account the difficulty to reach the upper estimate of the supply potential. As a result the assumed import potentials by 2050 are 150PJ for the low availability scenario, 400PJ for the medium availability scenario and 650PJ for the high availability scenario.

For 2030 it was assumed that less biomass would be available than in 2050 because the infrastructure required to produce and transport biomass takes time to be established. Therefore the assumed import potential is 100 PJ in the low scenario, 300 PJ in the medium scenario and 500 PJ in the high scenario. These values are also in the range of those assumed by Tsiropoulos et al. (2017).

5.4.3. Used cooking oil (UCO)

The consumption of UCO based biofuels in the Netherlands has experienced rapid historical growth, helped by the fact that biofuels produced from these waste resources are allowed to be double-counted towards the Renewable Energy Directive its transport blending targets (NEA, 2016). In 2017, 61% of the 19.5 PJ renewable transport fuels consumed in the Netherlands were based on UCO (NEA, 2018). Despite the fast historic increase of UCO based biofuel consumption in the Netherlands it seems unlikely that this trend will continue in the future. One reason for this is that the Netherlands is already one of the largest UCO importers (Greenea, 2017) and sustainable UCO supply may soon reach its limits. This is reflected by the fact that already in 2017 89% of the UCO consumed in the Netherlands had to be imported from 70 different foreign countries (NEA, 2018). More importantly, the use of UCO and animal fats as a feedstock for biofuel production was capped at 1.7% in the revised EU renewable energy directive (ICCT, 2018). It was therefore assumed that the future availability of UCO in the Netherlands would not be much higher than current consumption. Specifically, for both 2030 and 2050 and for all scenarios the availability of UCO (both domestically supplied and imported) was assumed to be 15 PJ.

Table 14: Assumed availability of sustainable biomass in the three scenarios.

Biomass availability (PJ primary energy)	**2030**			**2050**		
	Low	**Medium**	**High**	**Low**	**Medium**	**High**
Imports (wood pellets)	100	300	500	150	400	650
UCO (both domestically supplied & imported)	15	15	15	15	15	15
Domestically supplied (various kinds)	161	161	161	147	147	147
Total	276	476	676	312	562	812

In the remainder of this report all non-lignocellulosic kinds of biomass will be referred to as biomass (other).

5.5. Price of energy carriers

The prices of energy carriers that are allowed to be ‘bought’ by OPERA are shown in table 15. The price of UCO was estimated at €15.00 / GJ based on Greenea (2017). The prices of the other energy carriers were already present in the OPERA database and derived from the Dutch national energy outlook 2016 (Schoots et al., 2016). These were left unchanged. However, a sensitivity analysis for the price of biomass is included in the discussion. Also note that although the prices are noted with high precision in table 15, it is quite uncertain what the future price of energy carriers will actually be.

Table 15: prices of energy carriers that are allowed to be ‘bought’ by OPERA.

Energy carrier	**Price in 2030 (€ / GJ)**	**Price in 2050 (€ / GJ)**
Coal & cokes	2.83	3.24
Crude oil & LPG	13.56	14.40
Natural gas	8.22	8.20
Biomass (all kinds, except UCO)	6.71	6.71
UCO	15.00	15.00
Uranium	0.72	0.72
Waste	-9.00	-9.00
Wind, solar irradiation, environmental heat and geothermal heat	free	free

6. Model results

This chapter shows the optimal solution found by the model for each of the policy and biomass availability scenarios.

6.1. Reference scenario

Figure 21 shows the national energy demand in 2030 & 2050 for the reference policy scenario and each of the three biomass availability scenarios. Here the energy demand refers to the amount of energy carriers that were 'bought' by the system (and thereby entered the system boundaries). For both 2030 and 2050 the graph shows a high demand for crude oil & LPG in all three biomass availability scenarios. However, most (if not all) of this crude oil is used in non-energy related industrial processes or for refining into HFO and jet fuels. In both of these cases the consumption of crude oil does not result in GHG emissions that have to be counted towards the national emissions. In the case of the non-energy consumption of crude oil this is because the carbon contained in the crude oil ends up in the final product (e.g. plastics or chemicals) instead of being emitted as CO_2 into the atmosphere. In the case of the refining of bunker fuels the emissions are not counted as is consistent with current carbon accounting policies.

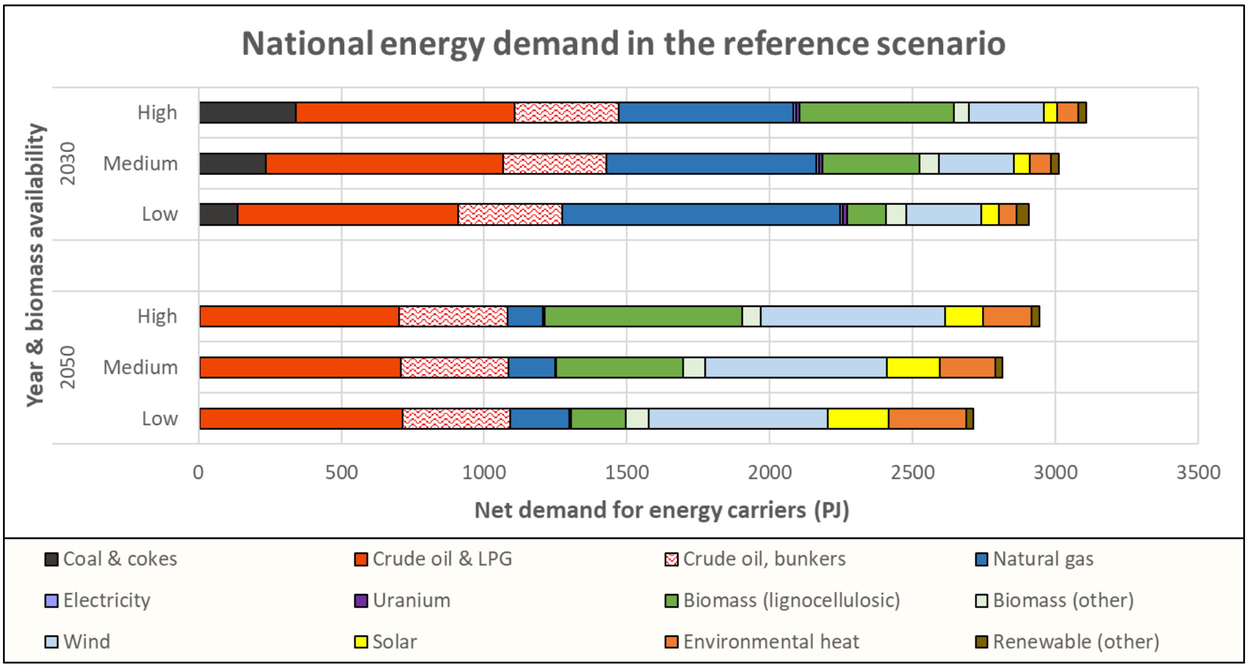

Figure 21: national 2030 & 2050 energy demand in the reference policy scenario for the three biomass availability scenarios.

In 2030 most energy related GHG emissions stem from the use of coal in power plants, cokes in the steel industry, crude oil for the production of transport fuels and natural gas in a variety of applications such as residential heating, electricity generation, transport and the ammonia industry. Non-energy related GHG emissions (primarily CH_4 and N_2O emissions in agriculture) are also significant. In all biomass availability scenario's these non-energy related GHG emissions add up to about 27 Mt CO_2-eq in 2030.

Achieving the 49% GHG reduction target in 2030 requires a large deployment of renewable energy sources in all biomass availability scenario's. Table 16 shows the deployment of biomass, wind, solar and CCS both in absolute values and as a percentage of their maximum potential in that scenario. Lignocellulosic biomass and wind power prove attractive energy sources given that they are used to their full potential in all scenarios. The deployment of solar energy and non-lignocellulosic biomass is also significant compared to its maximum potential but this differs between the biomass availability scenarios. Additionally, CCS is used to its maximum potential but this potential is still very low in 2030.

Table 16: deployment of biomass, wind power, solar power and CCS (as a percentage of their maximum potential) in 2030 and 2050 in the reference policy scenario.

Year	Biomass availability	Lignocellulosic biomass (PJ)	Other biomass (PJ)	Wind (GWe installed capacity)	Solar (GWe installed capacity)	CCS (Mt CO_2)
2030	Low	138 (100%)	70.0 (51%)	18.2 (100%)	22.7 (100%)	1.0 (100%)
	Medium	338 (100%)	70.0 (51%)	18.2 (100%)	19.1 (84%)	1.0 (100%)
	High	538 (100%)	52.9 (38%)	18.2 (100%)	16.4 (72%)	1.0 (100%)
2050	Low	192 (100%)	81.1 (67%)	46.4 (100%)	69.5 (100%)	25.0 (100%)
	Medium	442 (100%)	79.3 (66%)	46.4 (100%)	62.5 (90%)	25.0 (100%)
	High	692 (100%)	67.1 (56%)	46.4 (100%)	41.8 (60%)	25.0 (100%)

In 2030, lower availability of importable biomass increases the deployment of solar power and somewhat increases the use of other available biomass resources (UCO and coferment). More importantly, the fact that less renewable energy is available leads to the substitution of coal & cokes with natural gas. This is a result of the lower carbon intensity of natural gas compared to that of coal & cokes. By substituting coal and cokes with natural gas, more energy can be retrieved from fossil resources while maintaining the same GHG emissions. Furthermore, lower biomass availability reduces the total national energy demand which indicates that more efficient and demand-reducing options are deployed to keep GHG emissions within the allowable levels.

Table 17 shows the total system costs and the marginal GHG abatement costs in 2030. Here the total system costs consist of the costs of all options that are within the models system boundaries. The absolute system costs is therefore a somewhat arbitrary number because it depends fully on how the system boundaries in OPERA are defined. A comparison of the total system costs between scenarios does however provide a good indicator of how much the different conditions in a scenario affect the costs of the Dutch energy system. In the reference policy scenario, the total system costs increase by 1.67% if the biomass availability is low and decrease by 0.91% if the biomass availability is high (both compared to the medium biomass availability scenario).

The marginal GHG abatement costs show the costs of reducing the total system emissions by one additional unit on top of the target for that scenario. For the medium biomass availability scenario in 2030 this means that all options capable of reducing the total system emissions by one tonne CO_2-eq while increasing the total system costs by less than €87.90 will have been deployed by the model. Table 17 shows that the biomass availability has a large impact on the marginal GHG abatement costs. This means that more expensive ways to reduce GHG emissions become economically viable if there

Table 17: total system costs and marginal GHG abatement costs in the reference policy scenario. The percentages shown in the table show the change compared to the medium biomass availability scenario.

Year	Indicator	High		Medium	Low	
2030	Total system costs (billion €)	73.06	(-0.91%)	73.73	74.96	(+1.67%)
	Marginal GHG abatement costs (€ / tonne CO2-eq)	39.0	(-56%)	87.9	121.8	(+39%)
2050	Total system costs (billion €)	84.53	(-3.17%)	87.30	92.42	(+5.86%)
	Marginal GHG abatement costs (€ / tonne CO2-eq)	279.5	(-28%)	388.2	653.5	(+68%)

Figure 1 – 3 in appendix C show how the biomass in each of the three biomass availability scenario's is used. Since the emissions from IBFs are not accounted for in the reference policy scenario none of the biomass is used to produce marine or jet fuels. Instead the biomass is primarily used for the production of electricity, heat, biogas or biofuels used in road transport.

In 2050 the 95% GHG reduction target results in a large decrease in the consumption of fossil energy carriers. The consumption of coal is completely phased out while virtually all remaining crude oil and LPG demand originates from non-energy related processes or the refining of HFO and jet fuels. The consumption of natural gas has been greatly reduced and is now mostly used for the provision of heat in the built environment, although its application here has also declined much compared to 2030. The shift from fossil to low- or zero-carbon energy carriers goes hand in hand with the electrification of industry and the built environment using heat pumps. It is also aided by a reduction of the energy demand e.g. through insulation in the built environment. Non-energy related GHG emissions (e.g. CH_4 emissions in agriculture) are lower than in 2030 and now range from 20 Mt CO_2-eq in the high biomass availability scenario to 15 Mt CO_2-eq in the low biomass availability scenario. Nevertheless, this is a very significant amount given that the maximum allowable national GH emissions are only 11.2 Mt CO_2-eq.

Even though the potentials of biomass, wind, solar and CCS are much higher in 2050 compared to 2030, virtually all of this potential is utilized (table 16). The marginal GHG abatement costs in 2050 are much higher than in 2030. This indicates that the system is operating closer to its limits and more expensive options have to be deployed to achieve the 2050 GHG reduction target. The much higher CO_2 abatement cost in the low biomass availability scenario show that this is especially the case if little importable biomass is available.

Figure 4 – 6 in appendix C show that biomass is used mostly for the same end-purposes as in 2030. However, the higher potential of CCS means that options which can combine biomass consumption with CCS to reach negative GHG emissions are more frequently deployed.

6.2. Sector-specific policy scenario

Figure 22 shows how the national energy demand in 2030 changes in each of the biomass availability scenarios if the GHG emissions from IBFs are accounted for by setting sector-specific targets to limit their emissions. The results in the graph compare the national energy demand to that of the same biomass availability scenario in the reference policy scenario. Naturally, the consumption of crude oil decreases in all scenarios because a portion of the marine and jet fuels has to be produced from biomass to achieve the sector-specific GHG targets. This means that less biomass is available for the production of electricity, heat and biogas in the medium and high biomass availability scenarios. This causes a large increase in the consumption of natural gas for applications where biomass was previously used and a decrease in the consumption of coal to compensate for the emissions from the additional natural gas consumption. In the low biomass availability scenario almost all biomass is consumed by conversion processes that are required to produce the necessary amount of renewable marine and jet fuels. This is also illustrated in figure 7 – 9 in appendix C. In all biomass availability scenarios, the non-energy related GHG emissions do not noticeably deviate from those in the reference policy scenario.

Table 18 shows that the total system costs and marginal GHG abatement costs in 2030 are much higher for the low biomass availability scenario than for the other two scenarios. This indicates that the model is only barely able to find a solution in which all of the model constraints are met.

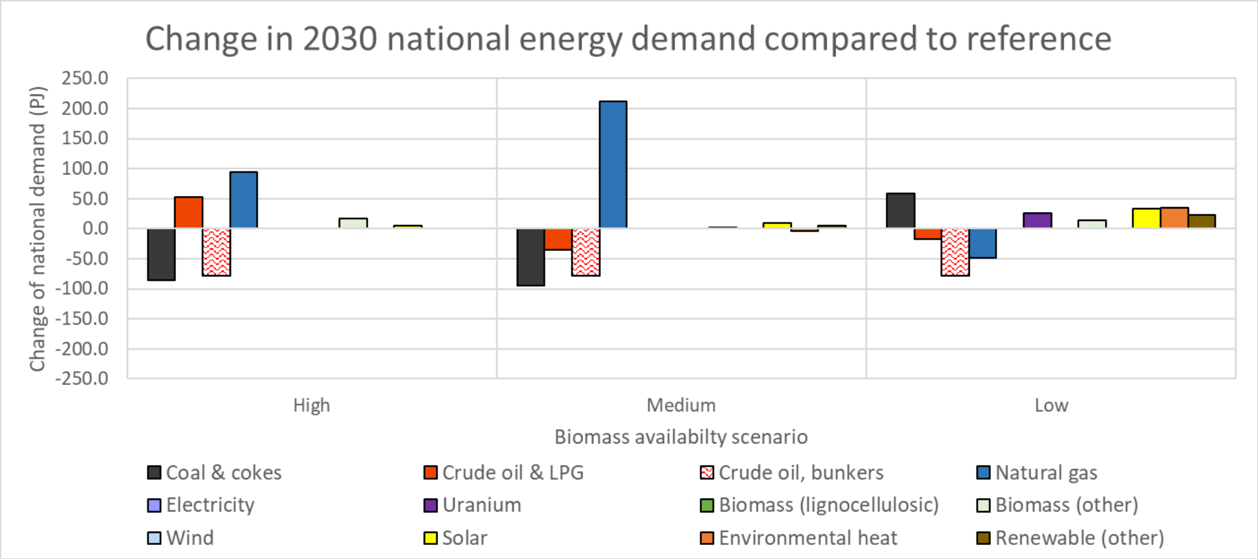

Figure 22: change of the 2030 national energy demand in the sector-specific policy scenario (sub-question 4) compared to the reference scenario

Table 18: total system costs and marginal GHG abatement costs in the sector-specific policy scenario. The percentages shown in the table show the change compared to the same biomass availability scenario in the reference policy scenario.

Year		High		Medium		Low	
2030	Total system costs (billion €)	74.24	(+1.62%)	75.37	(+2.22%)	94.00	(+25.40%)
	Marginal GHG abatement costs (€ / tonne CO2-eq)	77.1	(+98%)	108.8	(+24%)	444.5	(+265%)
2050	Total system costs (billion €)	89.06	(+5.35%)	94.82	(+8.61%)	-	
	Marginal GHG abatement costs (€ / tonne CO2-eq)	451.3	(+61%)	663.7	(+71%)	-	

In 2050, the stricter GHG emission reduction target for international shipping and aviation in combination with the overall higher demand for marine and jet fuels requires that a large amount marine and jet fuels has to be produced from renewable sources. The effects of this on the national energy demand are shown in figure 23. In the low biomass availability scenario there are simply not enough renewable energy sources available to supply this demand, so the model cannot find a solution. In the medium and high biomass availability scenarios a solution is possible. Here, the renewable marine and jet fuels are not only produced through biorefinery options, but also for a large part through power-to-liquids (see figure 10 & 11 in appendix C). This causes the deployment of expensive renewable energy sources elsewhere in the system. The deployment of these expensive options becomes economically viable because of the high marginal GHG abatement costs in both biomass availability scenarios (see table 18). Non-energy related GHG emissions are about 3 Mt lower in both biomass availability scenarios than in the reference policy scenario.

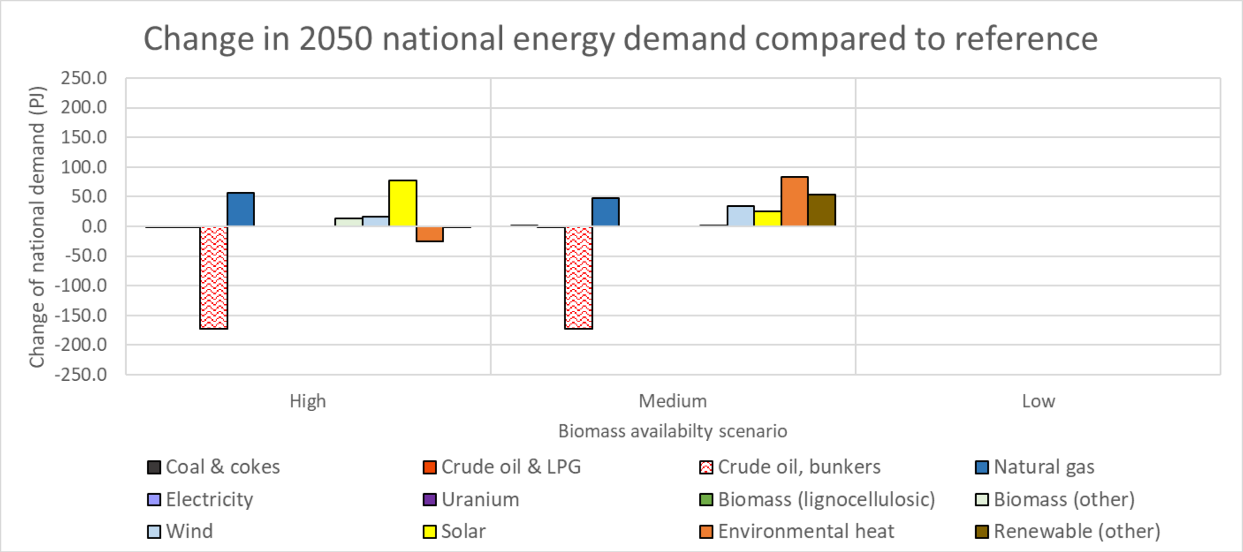

Figure 23: change of the 2050 national energy demand in the sector-specific policy scenario (sub-question 4) compared to the reference scenario.

6.3. IBF emissions included in national target

The fact that the GHG emissions from crude oil used to produce HFO and jet fuel are now included in the national GHG target means that much more GHG emissions have to be reduced in 2030 to achieve the 49% reduction target. Unlike in sub-question 4, these emissions do not necessarily have to be achieved by replacing HFO and fossil jet fuel with renewable alternatives. Figure 24 shows that this also does not happen in all three biomass availability scenarios since there are less expensive ways to reduce the GHG emissions. This comes primarily in the form of far-reaching decreases in the consumption of coal, natural gas and crude oil (for purposes other than HFO or jet fuel production). As a result of this, the total national energy demand needs to decrease in all biomass availability scenario's which is achieved through the deployment of more efficient and demand-reducing options. Table 19 shows that the costs resulting from this are very significant. Nevertheless, the non-energy related GHG emissions in this scenario are not much lower than in the reference scenario, indicating that OPERA has little options available in 2030 to reduce these emissions.

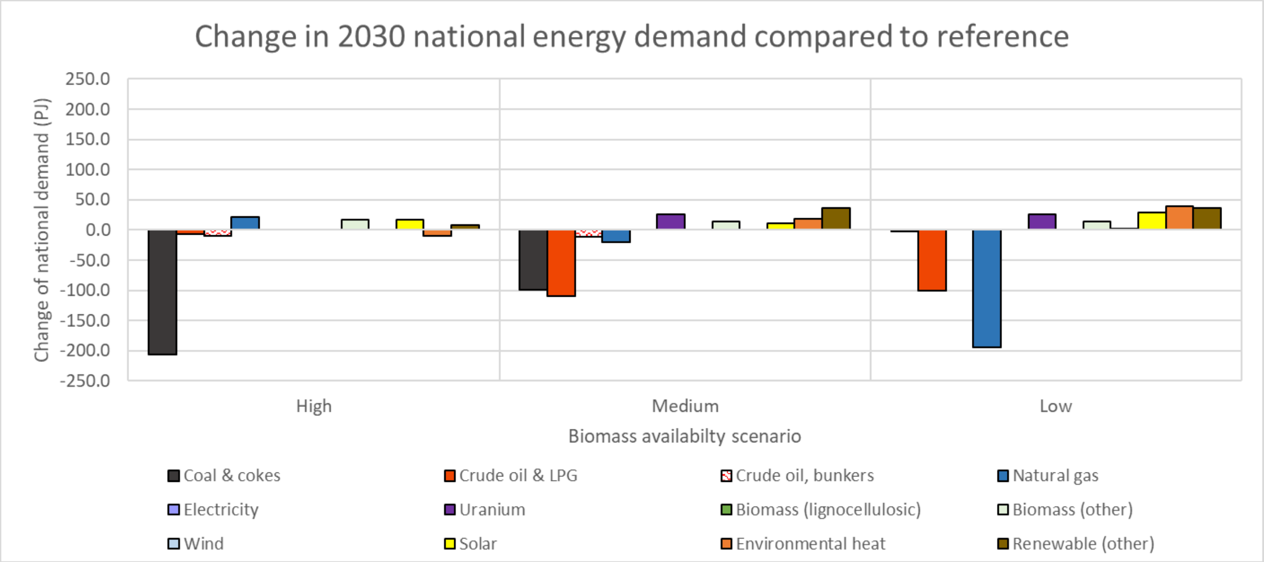

Figure 24: change of the 2030 national energy demand in the policy scenario where the emissions from IBFs are included in the national emissions (sub-question 5) compared to the reference scenario.

Table 19: total system costs and marginal GHG abatement costs in the policy scenario where the emissions from IBFs are included in the national emissions (sub-question 5). The percentages shown in the table show the change compared to the same biomass availability scenario in the reference policy scenario.

Year		High		Medium		Low	
2030	Total system costs (billion €)	74.99	(+2.64%)	77.21	(+4.73%)	83.79	(+11.77%)
	Marginal GHG abatement costs (€ / tonne CO2-eq)	193.4	(+396%)	393.9	(+348%)	1021.5	(+739%)
2050	Total system costs (billion €)	95.79	(+13.32%)	-		-	
	Marginal GHG abatement costs (€ / tonne CO2-eq)	1290.1	(+362%)	-		-	

Figure 12 – 14 in appendix C shows that the available biomass is not used much differently than in the reference policy scenario. This is a consequence of the fact that the production of biobased marine and jet fuels is not economically competitive to the other biomass consuming options.

In 2050, GHG emissions have to be reduced deeply to comply with the 95% reduction target. Because of this, the model could only find a solution in the high biomass availability scenario (figure 25). However, looking at the total system costs and marginal GHG abatement costs of this scenario (table 19) it is evident that even in this high biomass availability scenario a solution is only possible at unrealistically high costs.

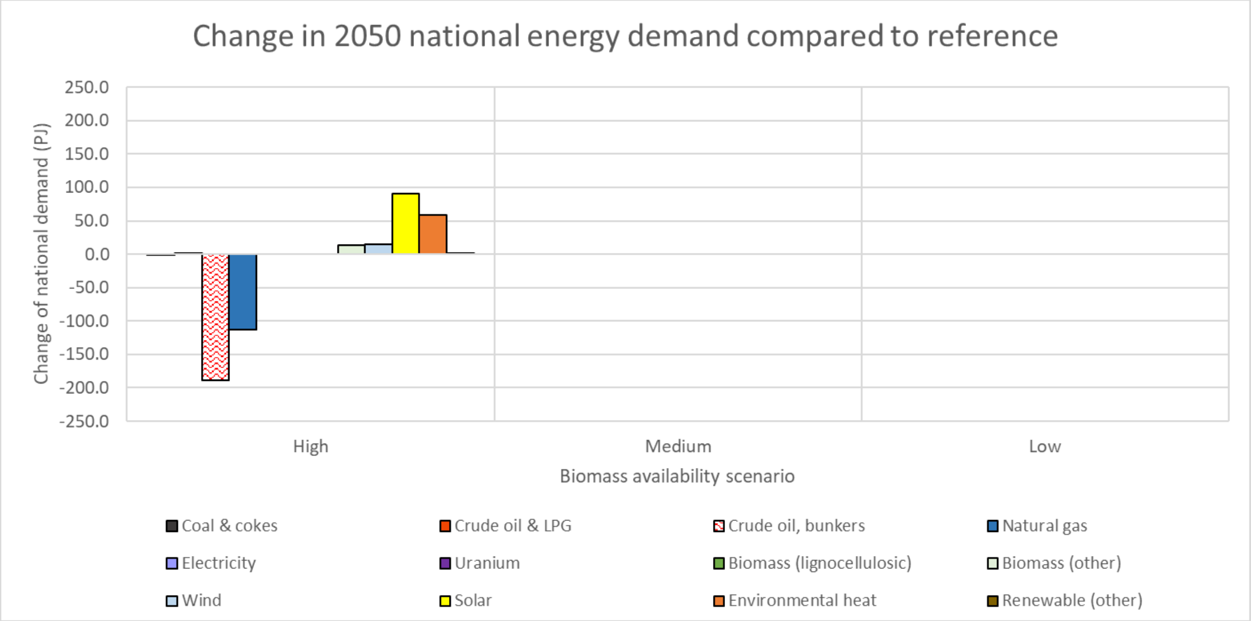

Figure 25: change of the 2050 national energy demand in the policy scenario where the emissions from IBFs are included in the national emissions (sub-question 5) compared to the reference scenario.

7. Discussion

Uncertainties about future technological, economic and political developments complicate long term forecasting studies such as this one and make their results inherently uncertain. This chapter therefore includes a sensitivity analysis in which some of the most important assumptions made during this study are changed in order to investigate their influence on the results in a quantitative manner. Additionally this chapter includes a qualitative discussion on the limitations and interpretability of the results, difficulties encountered during the study and recommendations for future research on the topic.

7.1. Sensitivity analysis

7.1.1. Projected marine and jet fuel demand

The projected demand for marine fuels in 2030 and 2050 was recalculated after varying the value of the most important assumptions as listed below. The results are shown in table 20.

1. The projected import & export demand growth in each year was varied by -0.50, +0.50 and +1.00 percentage point from the original value (original values are shown in table 3).
2. The assumed average distance covered by imported & exported freight was varied by -1500 & +1500 km from the original value of 8626 km.
3. The projected annual efficiency improvement was varied by +0.50, -0.50 and -1.00 percentage point from the original value of 1.83% per year.
4. The share of total freight that was transported by each type of vessel was assumed to remain the same as in 2016 rather than develop as in figure 7.

Table 20: sensitivity analysis results for the most important assumptions involved in the calculations of the Dutch demand for marine fuels. The percentages show the deviation from the original value.

Scenario		**2030**		**2050**	
Original Demand		177.9	(0%)	155.4	(0%)
Import & export growth	- 0.50 percentage point	166.1	(-7%)	131.3	(-16%)
	+ 0.50 percentage point	190.5	(+7%)	183.7	(+18%)
	+ 1.00 percentage point	204.0	(+15%)	217.0	(+40%)
Average shipping distance	- 1500 km	147.0	(-17%)	128.4	(-17%)
	+ 1500 km	208.8	(+17%)	182.4	(+17%)
Annual efficiency improvements	+ 0.50 percentage point	162.3	(-9%)	128.0	(-18%)
	- 0.50 percentage point	194.9	(+10%)	188.5	(+21%)
	- 1.00 percentage point	213.5	(+20%)	228.4	(+47%)
Share of freight transported per vessel type	Same as in 2016	164.9	(-7%)	134.9	(-13%)

The projected demand for jet fuels in 2030 and 2050 was recalculated after varying the assumed traffic growth and efficiency improvements as listed below. The results are shown in table 21.

1. The projected annual air traffic growth for both passenger and freight transport was varied by -1.00, +1.00 and +2.00 percentage point from the original values (shown in table 6).
2. The projected annual efficiency improvement of yet-to-be-built aircrafts were varied by +0.50 and -0.50 percentage point from the original values as described in chapter 4.4.3. The projected efficiency improvements of aircrafts that are already in production were left unchanged.

The average flight distance was not included in the sensitivity analysis since it was based on very detailed statistics in the case of passenger transport from which the largest share of the jet fuel demand originated. Given that the demand growth projection form Airbus (2018a) is much lower than the previously observed growth in the Netherlands this assumption was varied more than was done for the marine fuel sensitivity analysis. The results of the analysis are shown in table 21.

Table 21: sensitivity analysis results for the most important assumptions involved in the calculations of the Dutch demand for jet fuels. The percentages show the deviation from the original value.

Scenario		**2030**		**2050**	
Original value		166.1	(0%)	208.1	(0%)
Traffic growth	- 1.00 percentage point	146.4	(-12%)	150.9	(-27%)
	+ 1.00 percentage point	188.2	(+13%)	286.0	(+37%)
	+ 2.00 percentage point	213.0	(+28%)	392.0	(+88%)
Efficiency improvement of yet to be built aircrafts	+ 0.50 percentage point	160.9	(-3%)	182.3	(-12%)
	- 0.50 percentage point	171.3	(+3%)	237.4	(+14%)

An interesting result of the sensitivity analysis is that the effect of more or less strict efficiency standards in aviation have little effect on the 2030 fuel demand. This is because the jet fuel demand calculation took into account that efficiency improvements in yet-to-be-built aircraft would take time to be noticeable in practice. This time lag was not taken into account in the calculations of the marine fuel demand. There are however also much more operational efficiency improvements possible in shipping which are immediately noticeable, which somewhat justified this difference in the calculation process.

Other than that, the results from the sensitivity analysis show how a deviation of the assumed value for each of the assumptions has increasingly large effects on results further into the future. For example, of the air traffic demand growth is one percentage point lower or higher than the assumed value, which does not seem improbable, the jet fuel demand would already be 27% lower or 37% higher than what was projected in chapter 4.

7.1.2. Model results

To assess the influence of some of the assumptions made in OPERA the model results were recalculate after varying the value of some assumptions as listed below.

1. The price of biomass in both 2030 & 2050 was increased from €6.71 / GJ to €11.00 / GJ;
2. The potential of CCS in 2050 was varied from 25 Mt to 10 Mt and to 50 Mt in accordance with Ros & Daniëls (2017);
3. The potential of offshore wind in 2050 was increased from 40 GW to 80 GW in accordance with Ros & Daniëls (2017).

Price of lignocellulosic biomass

The price of wood pellets in Europe varied between €6.5 and €9.5 / GJ between 2009 and 2015 (OzForex, 2018), indicating that the currently assumed biomass price is in the correct range (albeit on the lower end of that range). However, it is possible that increased future competition would lead to a higher wood pellet price. To investigate the effect that this would have on the model results the model was rerun with a biomass price of €11.00 / GJ. The resulting GHG abatement costs and total system costs in 2030 and 2050 are shown in table 22.

Table 22: GHG abatement cost and total system costs in each scenario when the price of biomass is increased from €6.71 / GJ to €11.00 / GJ. The percentages show the percentage change compared to the results with a biomass price of €6.71 / GJ.

	Scenario	**Low biomass availability**	**Medium biomass availability**	**High biomass availability**
High price 2030				
Marginal GHG abatement costs (€ / tonne CO2-eq)	Q3	122 (0%)	89.0 (+1%)	79.4 (+104%)
	Q4	445 (0%)	109 (0%)	79.1 (+3%)
	Q5	1022 (0%)	413 (+5%)	193 (0%)
Total system costs (billion €)	Q3	75.60 (+0.84%)	75.22 (+2.02%)	75.24 (+2.98%)
	Q4	94.69 (+0.73%)	76.86 (+1.98%)	76.59 (+3.16%)
	Q5	84.48 (+0.82%)	78.74 (+1.97%)	77.34 (+3.13%)
High price 2050				
Marginal GHG abatement costs (€ / tonne CO2-eq)	Q3	653 (-0%)	393 (+1%)	280 (+0%)
	Q4	-	664 (+0%)	451 (0%)
	Q5	-	-	1290 (0%)
Total system costs (billion €)	Q3	93.34 (+1.00%)	89.26 (+2.24%)	87.55 (+3.57%)
	Q4	-	96.82 (+2.11%)	92.13 (+3.45%)
	Q5	-	-	98.86 (+3.21%)

The results show that in all-but-one scenario, the marginal GHG abatement costs remain roughly the same. This indicates that increasing the price of biomass in OPERA has little effect on which options are deployed by the model. The total system costs do increase noticeably, but this is simply because a higher price has to be paid for the same amount of biomass. It can be concluded that the price of biomass has little influence on the results of the scenarios in this research. Even with a high price, biomass is an attractive resource that is in many scenarios simply necessary to have sufficient renewable resources.

CCS potential

The GHG abatement costs and total system costs of a run with low (10 Mt) CCS potential and high (50 Mt) CCS potential in 2050 are shown in table 23 and 24. The results show that for all policy scenarios the model results are extremely dependent on the potential of CCS. So much so that if the potential of CCS is dropped from 25 Mt to 10 Mt in 2050, no solution is possible for most scenarios while the scenarios for which a solution could be found all show unrealistically high GHG abatement costs and total system costs. If the potential of CCS is low, GHG emissions that are difficult to be avoided (such as CH_4 and N_2O emissions in agriculture) can no longer be compensated for so that a solution is no longer possible. If the potential of CCS is increased to 50 Mt much more GHG emissions can be compensated for. This allows options whose GHG emissions are expensive to reduce to remain unchanged, significantly decreasing the GHG abatement costs and total system costs.

Table 23: GHG abatement costs and total system cost in each scenario when the potential of CCS is decreased from 25 Mt to 10 Mt. The percentages show the percentage change compared to the results with a CCS potential of 25 Mt.

Min CCS	Scenario	Low biomass availability	Medium biomass availability	High biomass availability
Marginal GHG abatement costs (€ / tonne CO2-eq)	Q3	-	4439.1 (+1044%)	3448 (+1134%)
	Q4	-	-	4802.9 (+964%)
	Q5	-	-	-
Total system costs (billion €)	Q3	-	101.36 (+16.10%)	93.06 (+10.09%)
	Q4	-	-	102.13 (+14.68%)
	Q5	-	-	-

Table 24: GHG abatement costs and total system cost in each scenario when the potential of CCS is increased from 25 Mt to 50 Mt. The percentages show the percentage change compared to the results with a CCS potential of 25 Mt.

Max CCS	Scenario	Low biomass availability	Medium biomass availability	High biomass availability
Marginal GHG abatement costs (€ / tonne CO2-eq)	Q3	500 (-23%)	213.8 (-45%)	196.6 (-30%)
	Q4	-	350.6 (-47%)	247.3 (-45%)
	Q5	-	500	326.5 (-75%)
Total system costs (billion €)	Q3	88.33 (-4.42%)	83.28 (-4.62%)	81.29 (-3.84%)
	Q4	-	90.06 (-5.02%)	85.29 (-4.22%)
	Q5	-	91.95	87.34 (-8.82%)

Offshore wind potential

The GHG abatement costs and total system costs for a run in which the potential of offshore wind is increased from 40 GW_e to 80 GW_e are shown in table 25. The effect is similar to the what is observed if more biomass is assumed available. The higher availability of renewable resources means that less efficient and less expensive options may be deployed and that fewer demand-reducing or GHG-reducing options need to be deployed. This reduces the costs of the energy system.

Table 25: GHG abatement costs and total system costs in each scenario when maximum capacity of offshore wind is increased from 40 GW_e to 80 GW_e. The percentages show the percentage change compared to the results with a maximum offshore wind capacity of 40 GW_e.

Max wind	Scenario	Low biomass availability	Medium biomass availability	High biomass availability
Marginal GHG abatement costs (€ / tonne CO2-eq)	Q3	500 (-23%)	328 (-16%)	210 (-25%)
	Q4	-	403 (-39%)	323 (-29%)
	Q5	-	859	555 (-57%)
Total system costs (billion €)	Q3	90.21 (-2.39%)	86.52 (-0.89%)	84.38 (-0.19%)
	Q4	-	91.23 (-3.79%)	87.39 (-1.87%)
	Q5	-	97.54	92.33 (-3.61%)

7.2. Qualitative discussion

Given the inherent uncertainty of many assumptions that had to be made during this study and always have to be made during long-term forecasting studies, the values presented in this research should not be interpreted as accurate predictions of the future. Rather than that the results of this research serve as an exploration of what would happen if certain developments would take place into the future and certain policies would be adopted.

Furthermore, this research is limited by its scope as mentioned in chapter 2.3. The fact that OPERAs foresight is limited to the year that is modelled means that the results shown for 2030 might not be on the right track towards an energy system that is suitable for 2050. The results of the policy scenario corresponding to sub-question 5 for example showed that most options producing drop-in marine or jet fuels were not competitive in 2030, but essential to achieve the GHG reduction targets in 2050. Policy makers should take this path-dependency into account and stimulate the development of these options even if they cannot be expected to be competitive on the short term. Lock-in effects not only occur on the supply side but also on the demand side as vehicle engines are built to burn a specific type of fuel.

The fact that only emissions within the Dutch borders (with the exception of emissions from the combustion of bunker fuels) were included in the research is fair in respect to the current IPCC accounting methodology (IPCC, 2006). However, it should be considered that resources imported from abroad may cause significant chain emissions abroad during cultivation, mining, processing or transport. This is especially the case for biomass, whose chain emissions are often larger than those of other energy carriers (Ros et al., 2011). If these chain emissions were accounted for, the model results could change significantly. Furthermore, the actual climate impact of GHG emissions might differ depending on the location in the atmosphere where the emissions take place. Cirrus clouds originating from aircraft emissions likely have a warming effect on the climate while aerosols emitted by ships likely have a cooling effect (Lee et al., 2009; CCC, 2011). But the scientific consensus on this topic is still weak.

The Dutch energy system in OPERA is modelled as a more closed system than it actually is. A consequence of this is that biofuels have to be produced within the Netherlands while they could in reality also be imported from abroad. Although this would provide an additional renewable fuel that could be imported by the Netherlands, this would also increase the domestic biomass consumption of exporting countries and thereby reduce the Dutch import potential of lignocellulosic biomass. As a result, the net amount of biofuels available to the Netherlands might not change because of this.

A key difference between the ambitions of the IMO & ICAO and those set in sub-question 4 is that the IMO & ICAO allow CO_2 emissions to be achieved through a combination of measures including fuel substitution, efficiency improvements and carbon offsetting. In this research, fuel substitution is the only one of these measures that was added as an option to the OPERA model. Efficiency improvements were included in the marine and jet fuel demand projections but thereby incorporated exogenous of the model. This means that no extra efficiency improvements could be achieved through additional investments. This might actually be a good representation of reality since it is difficult for one country to achieve such efficiency improvements. International carbon offsetting was completely left out of the research given the national scope of the OPERA model. However, it could be argued that carbon offsetting may not be a viable long-term solution anyway. As countries across the world move towards achieving their ambitious 2050 GHG reduction targets, carbon offsets will become more scarce and expensive. It therefore remains to be seen how much carbon offsets are available to compensate future emissions from shipping and aviation.

Furthermore, it was not taken into account that certain drop-in fuels have *blend walls* meaning that they cannot be mixed above a certain percentage with conventional fuels in engines. If these blend walls were taken into account, this would have made it even more difficult to achieve the GHG reduction targets in the 2050 scenarios.

Recommendations:
The sensitivity analysis showed that the model results are influenced a lot by the assumed potential of CCS. It seems as if this potential is currently just an arbitrarily assumed value. Given how large the influence of CCS on the end results is it would be useful to do additional research on this subject and improve the model with these new findings.

As was discussed in chapter 5.2., certain biobased drop-in fuels were allowed to be converted into other kinds of biobased drop-in fuels for the purpose of this research to prevent that the model would stop working simply because it was overproducing a particular type of drop-in fuel. This however may have caused that the biorefinery options are now represented much more flexible than they are in reality. If it would be possible to adjust the model so that flexibility in the kinds of outputs can be incorporation into the (bio)refinery options this would enhance the quality of the model.

Furthermore, the way that the costs of biomass are currently incorporated into the model (as a flat price for all different kinds of biomass) is quite simplistic. A better representation of reality would be if more valuable kind of biomass would be more costly to be bought by the model.

8. Conclusion

This study projected the future Dutch demand for marine and jet fuels and investigated how the inclusion of the emissions from these fuels in Dutch GHG reduction targets would affect the most cost-efficient setup of the Dutch energy system in 2030 and 2050. According to the allocation approach used in this study the Netherlands was responsible for a demand of 165 PJ marine fuels and 132 PJ jet fuels in 2016. Although this demand is quite large compared to the total energy demand of the country, it is much smaller than the actual amount of bunker fuels that are sold in the Netherlands. This shows how allocation on the basis of the country in which the bunker fuels are sold would disadvantage countries that provide hub functions for international shipping and aviation.

The Dutch demand for marine fuels is expected to increase slightly to 178 PJ in 2030 after which a decrease in demand towards 155 PJ in 2050 is expected. This is primarily because the fuel savings due to efficiency improvements are expected to exceed the additional fuel demand due to import and export growth in the future. The Dutch demand for jet fuels on the other hand is expected to continue increasing, from 166 PJ in 2030 towards 208 PJ in 2050. Although future growth rates are expected to be much lower than those observed over the past 20 years, future passenger and freight demand growth are still expected to surpass future fuel efficiency savings by far. It should be noted however that long-term demand projections such as those presented in this study are inherently uncertain and depend much on the assumed growth rates, efficiency improvements and other assumptions.

The model results of the reference policy scenario show that if the emissions from IBFs remain excluded from Dutch GHG emission targets, significant efforts still have to be made to achieve the these targets. Domestic renewable energy resources are limited in the Netherlands and quickly used to their maximum potential. If more biomass can be imported this increases the available amount of renewable energy resources. This in turn prevents that expensive options that reduce the energy demand or decrease non-energy related GHG emissions have to be deployed. The expenses saved this way are much larger than the costs of the imported biomass, even if a high biomass price is assumed.

If the GHG emissions from IBFs are included in the Dutch GHG emission targets this requires that a large additional amount of GHG emissions are reduced. In 2030, some of this additional reduction can still be achieved by substituting coal with natural gas or renewables. In 2050, additional GHG emission reductions are much harder to achieve given that already few fossil energy carriers were consumed in the reference policy scenario. As a result, meeting the Dutch energy demand in 2050 while accounting for the GHG emissions from IBFs is only possible in scenarios where much biomass is available to be imported. If little biomass can be imported, meeting all energy demands while complying with the GHG emission targets is simply not possible.

A comparison of the results of sub-question 4 and 5 shows that in 2030, biomass will only be used for the production of drop-in marine and jet fuels if this is required by a sector-specific GHG reduction target for IBFs. This shows how the technologies to produce drop-in marine and jet fuels from biomass (with the exception of HEFA) are not competitive with other biomass consuming options (such as electricity generation) in 2030. This is either because the other options are less expensive or because they reduce more GHG emissions for the same amount of biomass consumed.

In 2050, most of the available biomass has to be used for the production of drop-in marine and jet fuels. This is necessary because drop-in marine and jet fuels can only be produced from biofuels or through power-to-liquid technology, the latter of which is limited by the availability of renewable electricity. Striving for the development of biorefinery technologies today can thus be useful – even if they are not competitive on the short term – given that these technologies are necessary to achieve the 2050 GHG emission targets.

Besides the importance of the available amount of importable biomass this study showed that the ability to achieve the 2050 GHG reduction targets depends very much on the assumed potential of CCS. When this potential was assumed to be 10 Mt instead of 25 Mt in 2050, most scenarios in this research (including even one reference scenario) could not be solved. Furthermore this study showed that in many scenarios not the costs of an option but its efficiency in terms of resource consumption and GHG reduction determined its competitiveness. As a result, biorefinery options combined with CCS – although expensive – were considered very attractive in some of the 2050 scenarios.

On a final note, considering how difficult it was to achieve the GHG emission targets in most scenarios, the question should be asked whether the demand for IBFs cannot be brought down from what was projected in this study.

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Appendix A: calculation of the specific fuel consumption of air freight transport in freighters

Freighter type	**Amount of movements**	**Maximum payload** (tonnes per movement)	**Transported weight at maximum payload** (tonnes, all movements)	**Assumed actual payload** (tonnes, all movements)	**Design range** (km)	**Traffic at design range and actual load** (RTK, all movements)	**Assumed actual flight distance** (km)	**Fuel consumption at actual payload & flight distance** (kg jet fuel per movement)	**Specific fuel consumption** (kg jet fuel per RTK)
Calculation	*From Schiphol (2016)*	*From aircraft manufacturers*	*Movements * max payload*	*Weight at max payload * load factor*	*From aircraft manufacturers*	*Movements * actual payload * design range*	*Design range * flight distance as % of design range*	*From EEA (2017b)*	*FC at actual payload & flight distance / (actual payload * flight distance)*
Boeing 777-200	6249	102.01	637460	359308	9200	3305630143	9435	66360	0.122
Boeing 747-400	5951	112.99	672403	379003	5910	2239910163	6061	66808	0.173
Boeing 747-8	2306	137.70	317536	178981	7630	1365623374	7825	92890	0.153
Airbus A300	1248	48.10	60029	33836	7500	253766381	7691	49505	0.237
Boeing 757-200	534	32.76	17491	9859	5000	49294904	5128	22854	0.241
Embraer EMB 120	396	3.32	1315	741	1481	1097492	1519	1309	0.460
MD11	289	86.53	25006	14095	6045	85202813	6199	62033	0.205
Boeing 737-400	274	17.09	4683	2639	3334	8798715	3419	11990	0.364
Airbus A330-200	202	65.00	13130	7401	7400	54765821	7589	49869	0.179
Boeing 737-300	132	19.73	2604	1468	3028	4445208	3105	10117	0.293
Airbus A330-300	78	60.00	4680	2638	7778	20517619	7976	50191	0.184
Boeing 747-200	56	110.13	6167	3476	6695	23273623	6866	83313	0.195
Boeing 767-300	54	52.48	2834	1597	6025	9624048	6179	35091	0.192
Airbus A310	34	39.00	1326	747	5950	4447067	6102	31233	0.233
Bae 146/AVRO RJ	2	9.50	19	11	2255	24150	2313	7002	0.566
		SUM	1766684		**SUM**	7426421523			
			--------------------------------			---------------------------------			
	Actual transported weight		995800	Actual traffic		7615873856			
	Resulting load factor		56.4%	Resulting flight distance (as % of design range)		102.6%			

Calculation of the specific fuel consumption of freight traffic by freighters

Appendix B: assumed annual fuel efficiency improvement

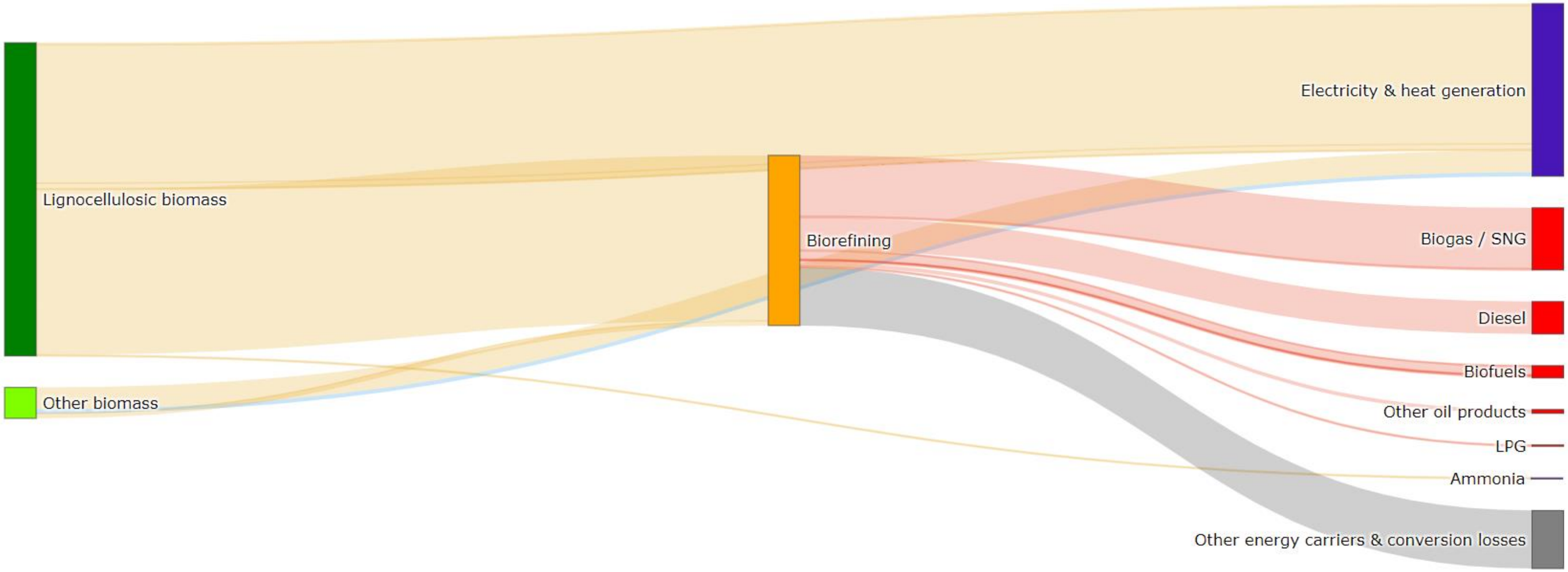
Year	Passenger aircrafts	Freighters
1990	-2.6%	+0.4%
1991	-2.6%	+0.4%
1992	-2.6%	+0.4%
1993	-2.6%	+0.4%
1994	-2.6%	+0.4%
1995	-2.6%	+0.4%
1996	-2.6%	+0.4%
1997	-2.6%	+0.4%
1998	-2.6%	+0.4%
1999	-2.6%	-2.6%
2000	-0.8%	-2.6%
2001	-0.8%	-2.6%
2002	-0.8%	-2.6%
2003	-0.8%	-2.6%
2004	-0.8%	-2.6%
2005	-0.8%	-2.6%
2006	-0.8%	-2.6%
2007	-0.8%	-2.6%
2008	-0.8%	-2.6%
2009	-0.8%	-0.8%
2010	-0.5%	-0.8%
2011	-0.5%	-0.8%
2012	-0.5%	-0.8%
2013	-0.5%	-0.8%
2014	-0.5%	-0.8%
2015	-0.5%	-0.8%
2016	-0.5%	-0.8%
2017	-0.5%	-0.8%
2018	-0.5%	-0.8%
2019	-0.5%	-0.5%
2020	-1.1%	-0.5%
2021	-1.1%	-0.5%
2022	-1.1%	-0.5%
2023	-1.1%	-0.5%
2024	-1.1%	-0.5%
2025	-1.1%	-0.5%
2026	-1.1%	-0.5%
2027	-1.1%	-0.5%
2028	-1.1%	-0.5%
2029	-1.1%	-1.1%
2030	-1.1%	-1.1%
2031	-1.1%	-1.1%
2032	-1.1%	-1.1%
2033	-2.0%	-1.1%
2034	-2.0%	-1.1%
2035	-2.0%	-1.1%
2036	-2.0%	-1.1%
2037	-2.0%	-1.1%
2038	-2.0%	-1.1%
2039	-2.0%	-1.1%
2040	-2.0%	-1.1%
2041	-2.0%	-1.1%
2042	-2.0%	-2.0%
2043	-2.0%	-2.0%
2044	-2.0%	-2.0%
2045	-2.0%	-2.0%
2046	-2.0%	-2.0%
2047	-2.0%	-2.0%
2048	-2.0%	-2.0%
2049	-2.0%	-2.0%
2050	-2.0%	-2.0%

Based on	
🟨	ICCT (2015)
🟧	Extrapolation of ICCT (2015)
🟩	ICAO CO2 emission standard

fc in reference to 2015		
Year	Passenger aircrafts	Freighters
1990	141.6%	133.3%
2016	99.5%	99.2%
2030	86.8%	90.8%
2050	59.0%	67.0%

Appendix C – consumption of biomass and synthetic fuels in individual scenarios *, **

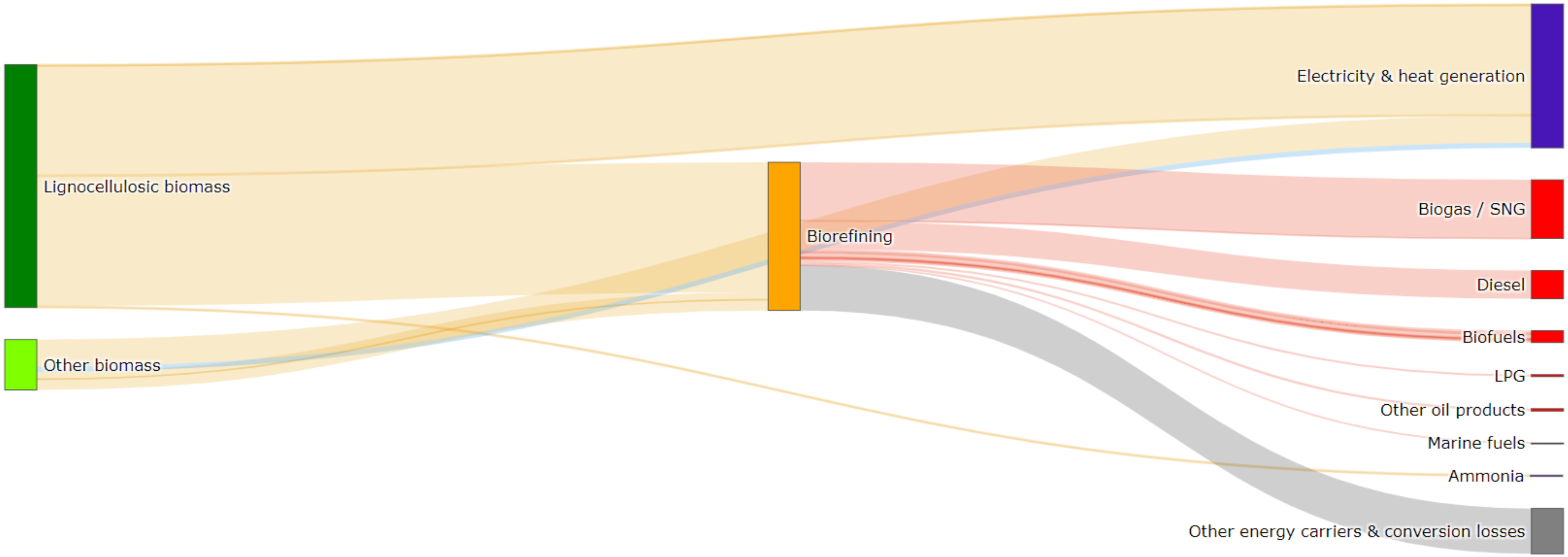
1: Reference scenario (sub-question 3), 2030, high biomass availability



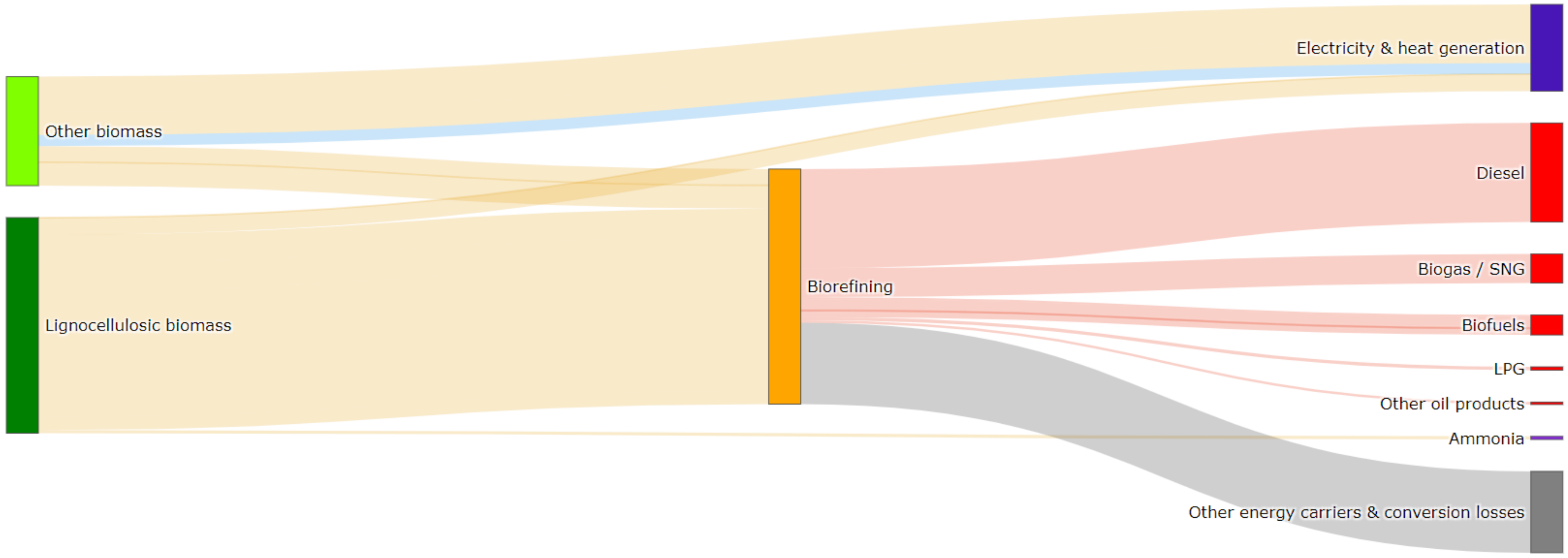
*The energy consumption of options combined with CCS is shown in blue

** The fuel outputs shown in these graphs represent drop-in fuels replacing a particular type of fossil fuel. So for example, the depicted flow of diesel represents drop-in fuels replacing fossil diesel.

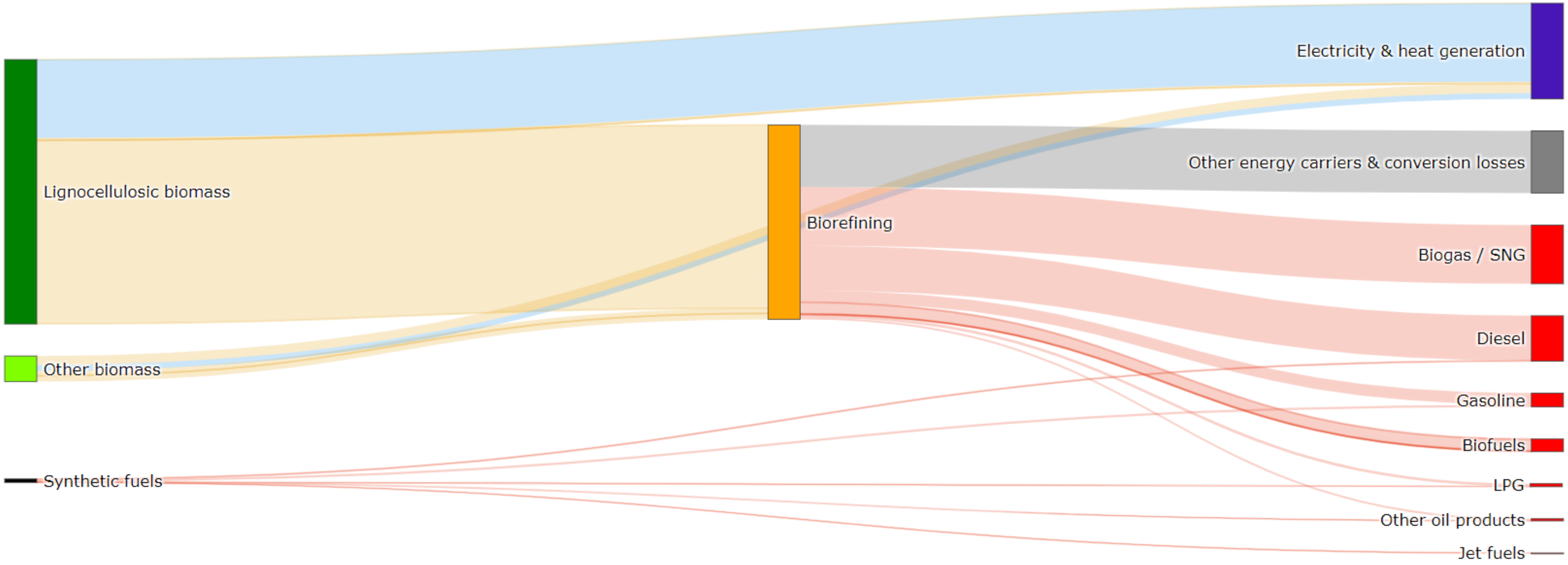
2: Reference scenario (sub-question 3), 2030, medium biomass availability



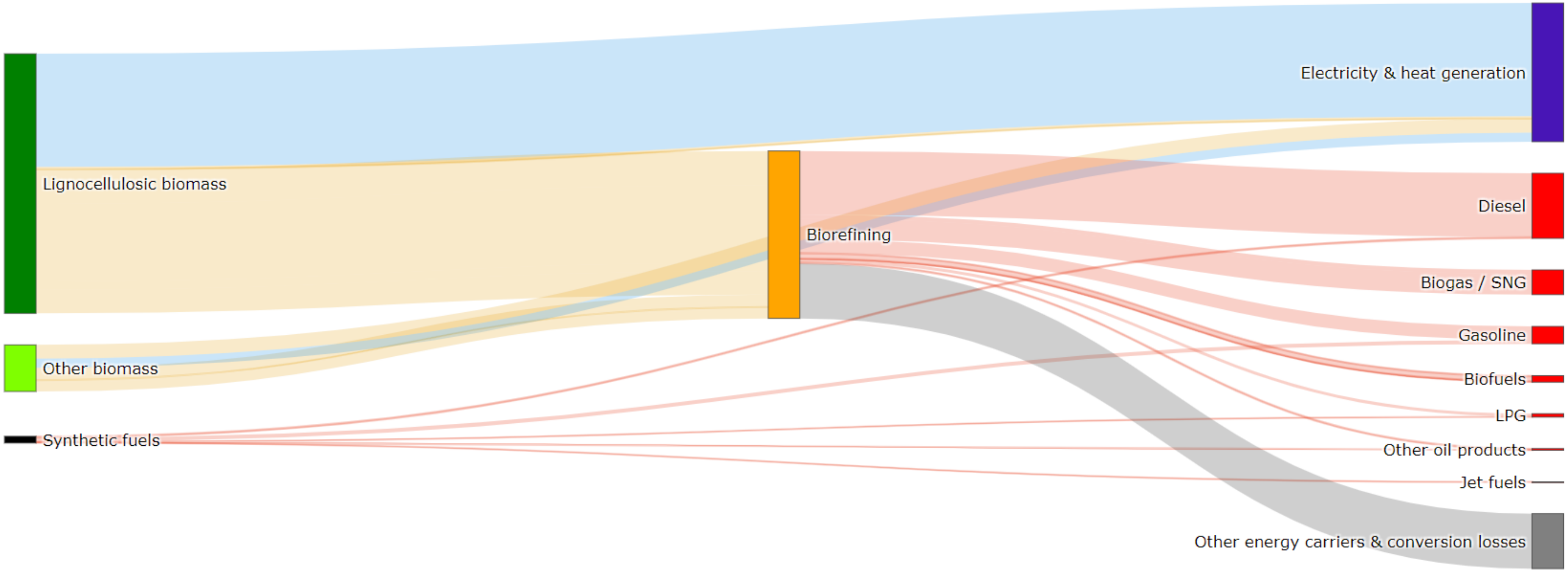
3: Reference scenario (sub-question 3), 2030, low biomass availability



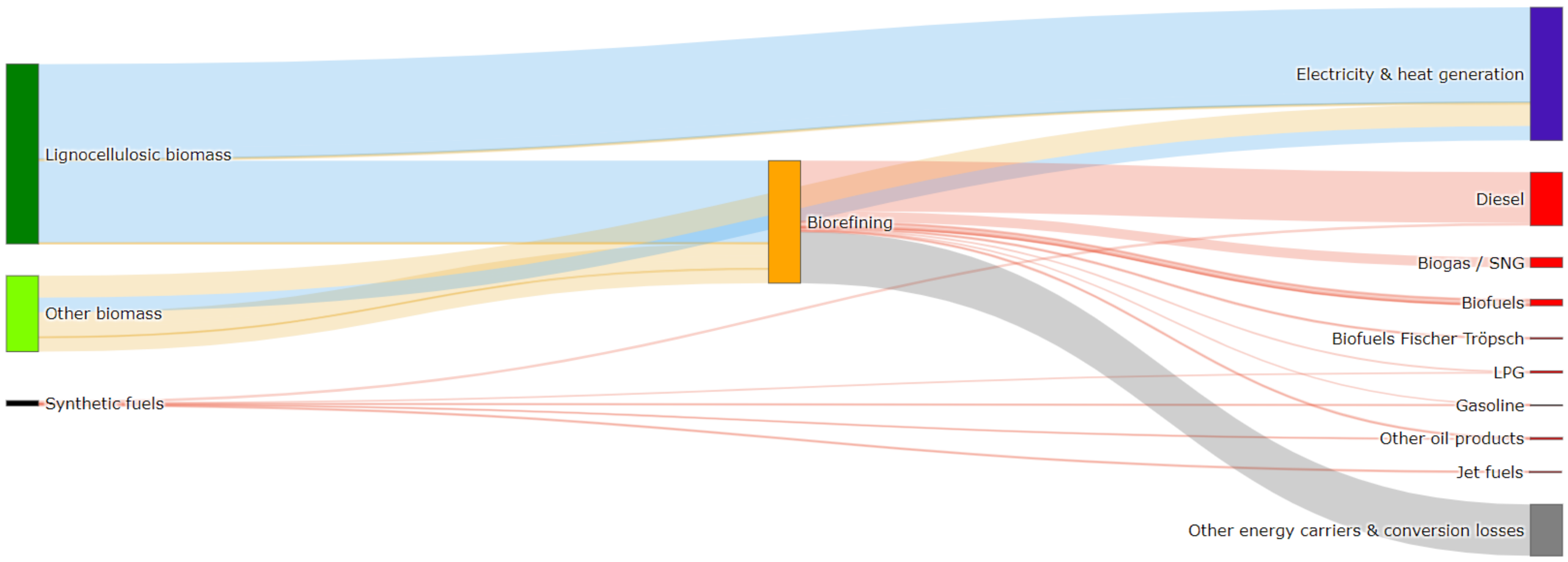
4: Reference scenario (sub-question 3), 2050, high biomass availability



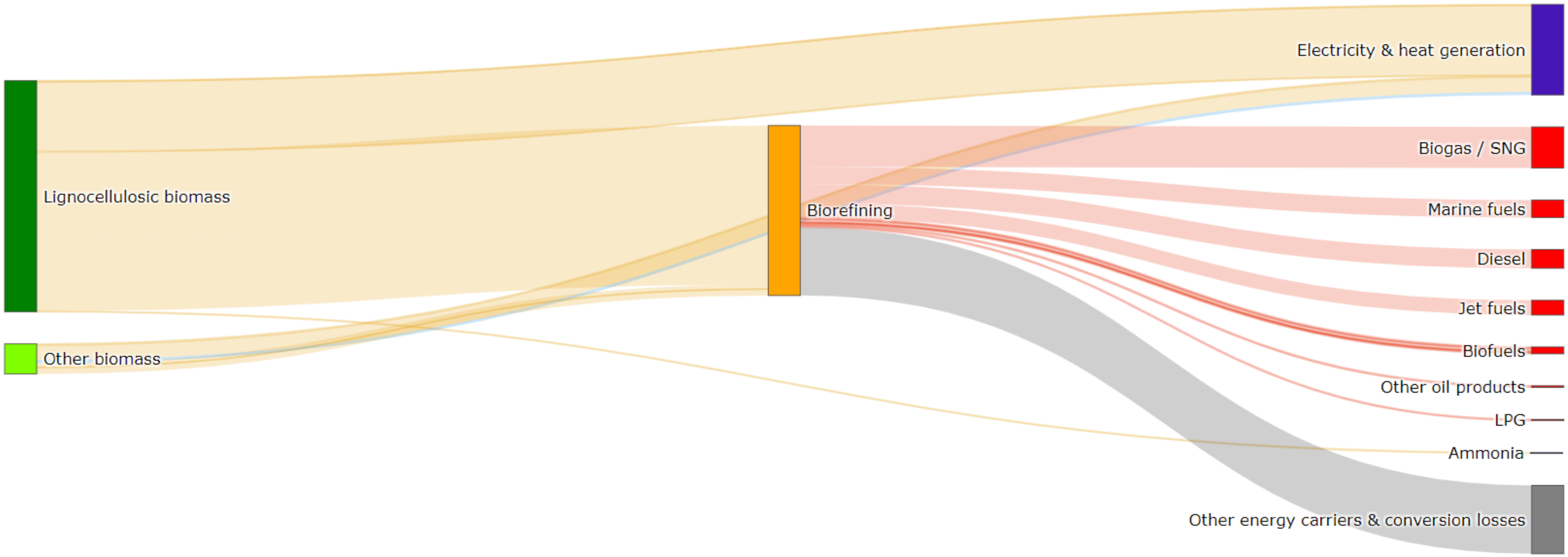
5: Reference scenario (sub-question 3), 2050, medium biomass availability



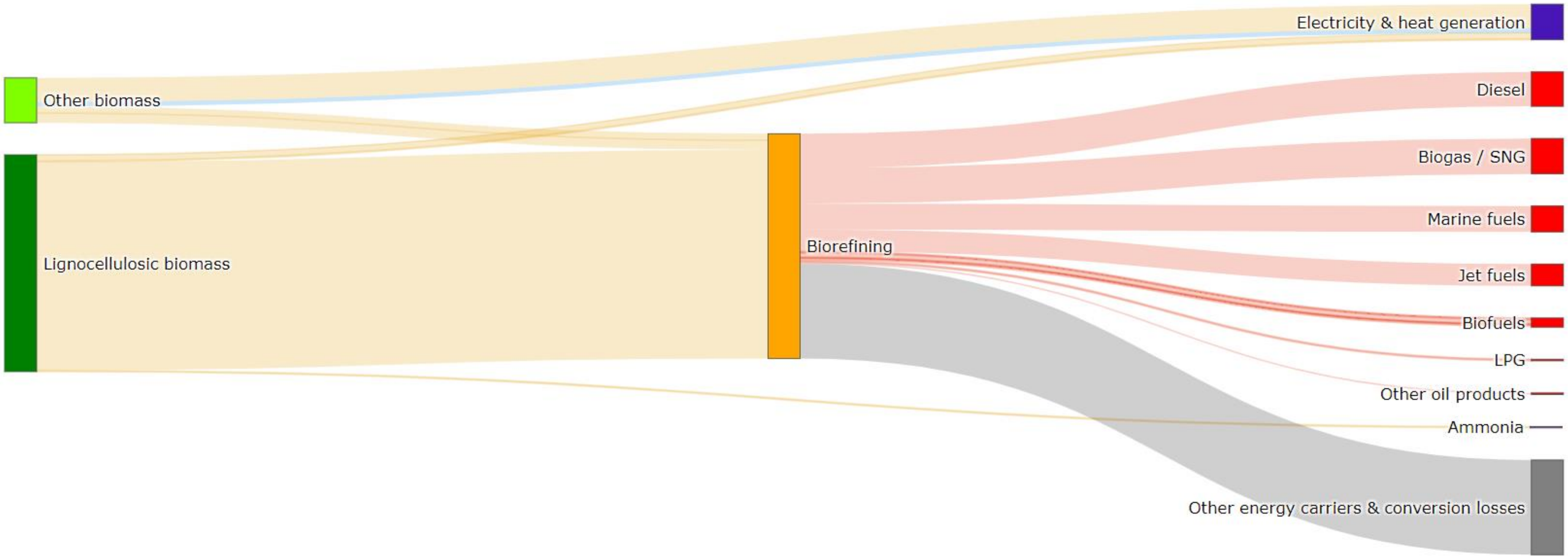
6: Reference scenario (sub-question 3), 2050, low biomass availability



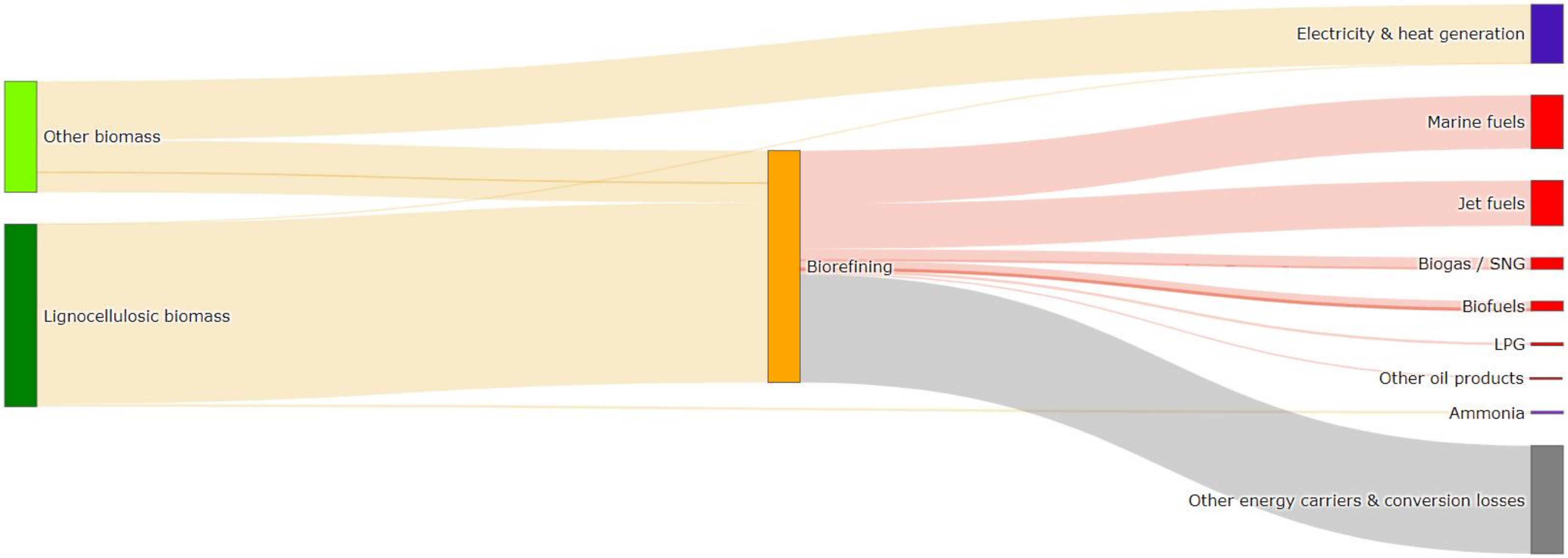
7: Sector-specific policy scenario (sub-question 4), 2030, high biomass availability



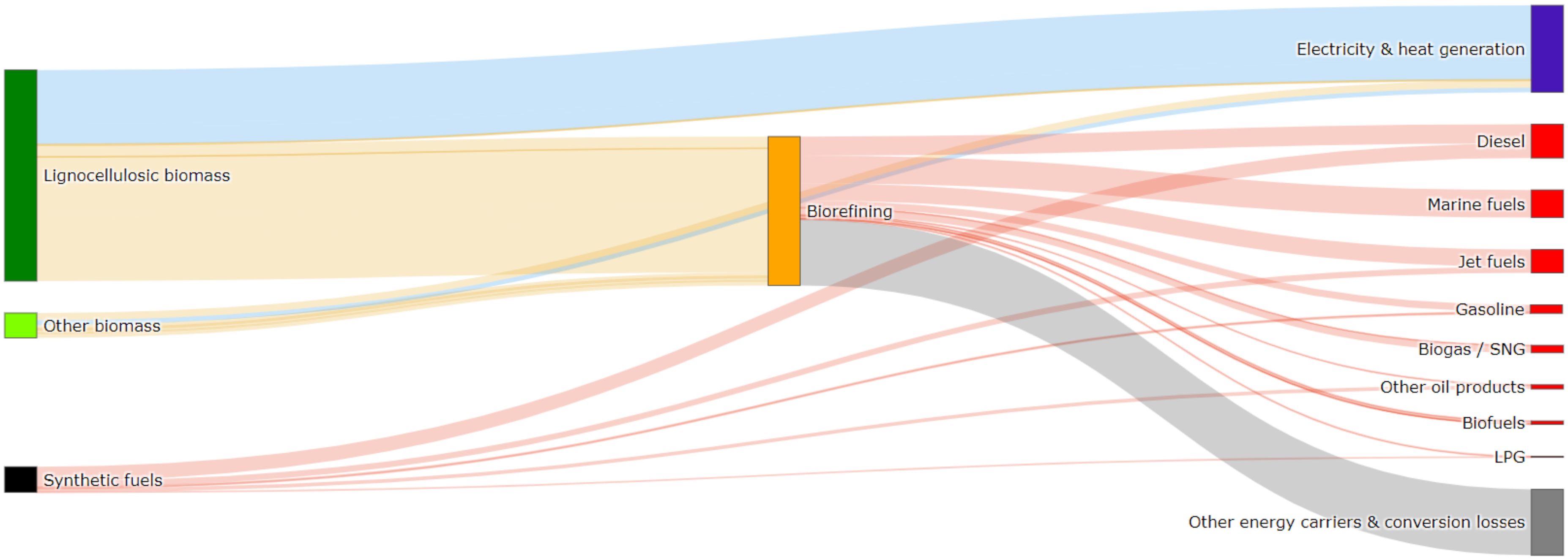
8: Sector-specific policy scenario (sub-question 4), 2030, medium biomass availability



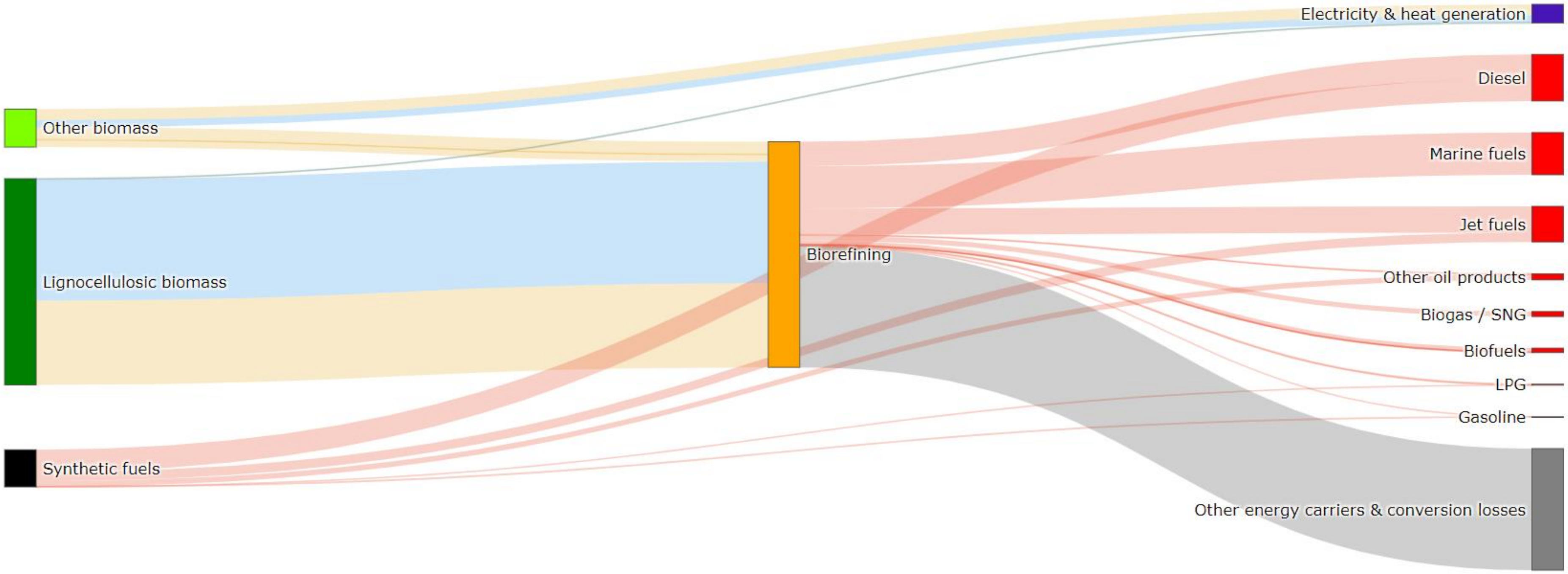
9: Sector-specific policy scenario (sub-question 4), 2030, low biomass availability



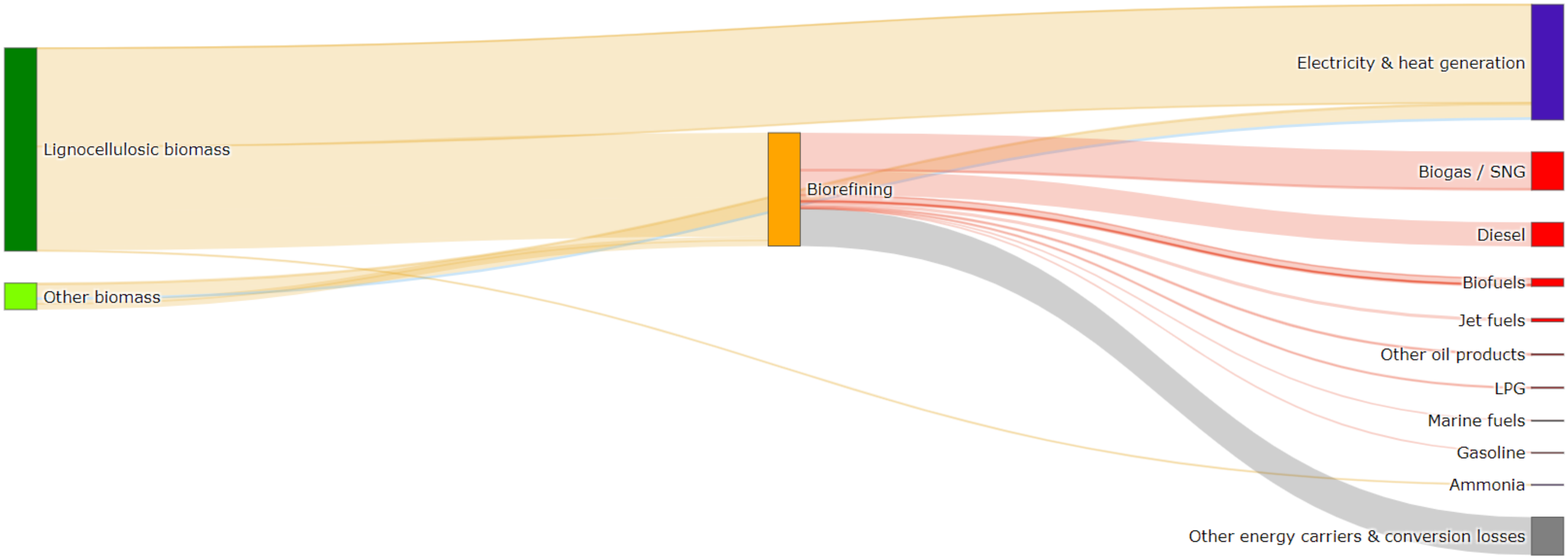
10: Sector-specific policy scenario (sub-question 4), 2050, high biomass availability



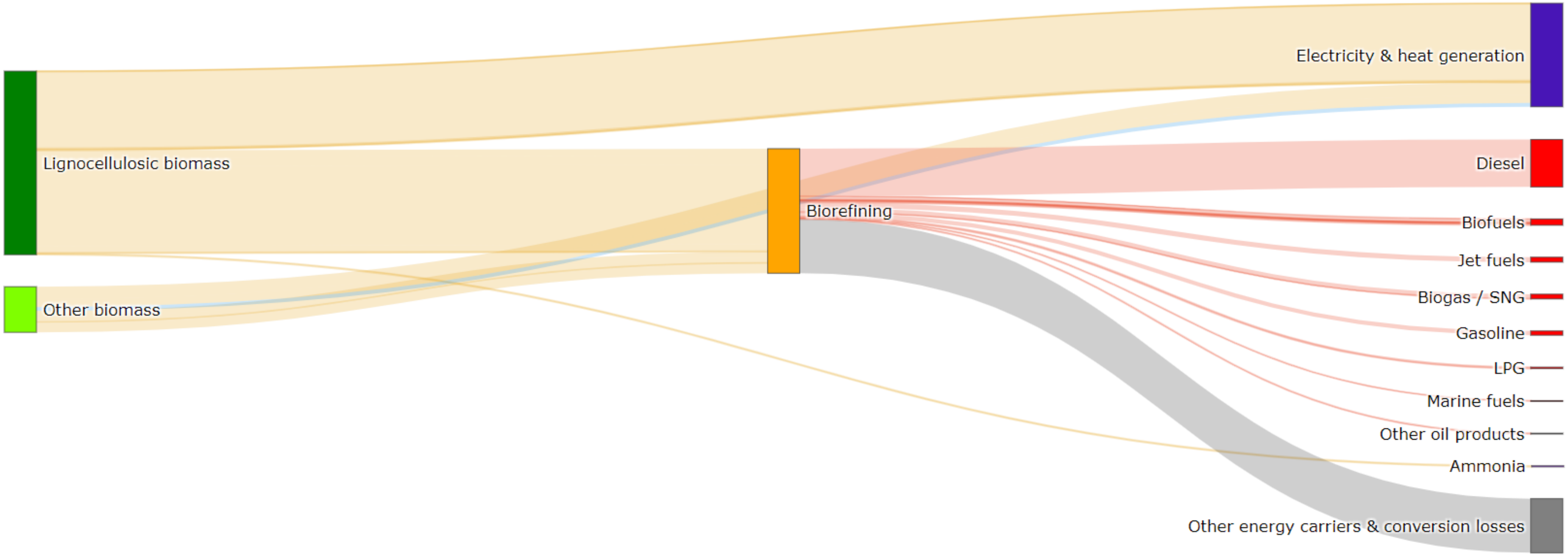
11: Sector-specific policy scenario (sub-question 4), 2050, medium biomass availability



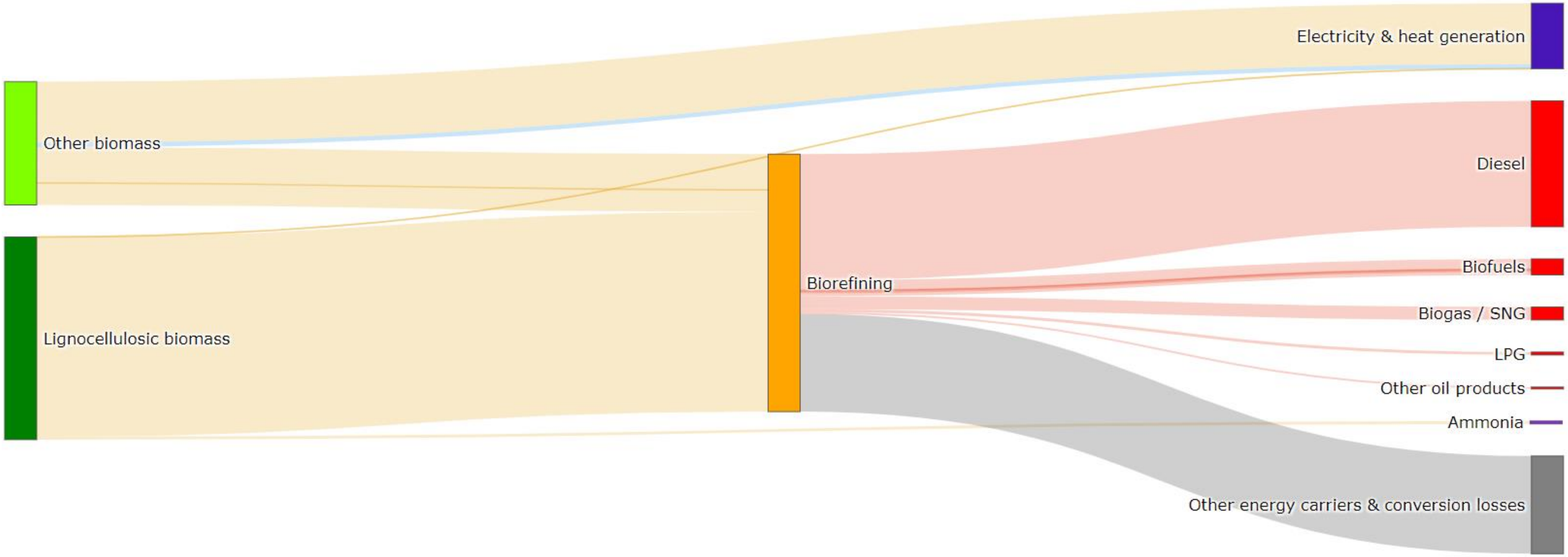
12: IBF emissions included in national target (sub-question 5), 2030, high biomass availability



13: IBF emissions included in national target (sub-question 5), 2030, medium biomass availability



14: IBF emissions included in national target (sub-question 5), 2030, low biomass availability



15: IBF emissions included in national target (sub-question 5), 2050, high biomass availability