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Feedstocks for sustainable aviation fuels in the Netherlands

A review of feedstock sustainability and availability and identification of knowledge gaps for policy making

Kennis voor Beleid Programma

Royal NLR – Netherlands Aerospace Centre

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Reducing aviation’s carbon footprint is critical to achieve global emission reductions as outlined in the Paris Climate Agreement and European emission reductions as outlined in the European Green Deal. Therefore, the aerospace industry is exploring various measures to reduce emissions. Sustainable aviation fuels (SAF) have recently seen increased attention as possible additional measure of reducing net CO_2 emissions from aviation.

The total potential contribution SAF can make to the decarbonisation of the aviation sector depends on the availability of SAF. This, in turn, depends on the availability of feedstocks: biomass for biofuels and (renewable) energy for e-fuels, primarily.

Description of work

This research identifies the most promising feedstocks for the production of large quantities of SAF in the Netherlands towards 2050, based on availability and sustainability of feedstocks sourced from the Netherlands or Europe for the production of SAF in the Netherlands in the 2050 timeframe. The results are contextualised by comparing possible supply to demand, by commercial international flights departing from the Netherlands.

Additionally, this research identifies areas in which additional research is needed to make informed policy decisions and makes policy recommendations. This focusses on the potential and need for SAF deployment and on energy planning.

Results and conclusions

This research shows the availability of feedstocks for biofuels in the Netherlands in 2050 is expected to be far lower than the range of demand for aviation, as based on WLO-scenarios. Trade within the EU – primarily France, Germany, Sweden and Ukraine – could cover that deficit, although the sustainability of transporting feedstocks, dependency on other countries for fuel and the (uncertain) willingness of those countries to trade make this option less desirable than national production.

Projected aviation energy demands by 2050 could be met by producing e-fuels from possible excess renewable energy produced in the Netherlands – defined as the difference between potential supply and anticipated demand. If less renewable energy is available for the aviation sectors, it is possible that not all demand may be covered.

Applicability

The results are applicable to the Netherlands and are based on information available to the authors at the moment of writing. Due to the inherent uncertainty associated to 30-year future projections, as well as specific uncertainties on future allocation of renewable feedstock to the aviation sector, results must be interpreted cautiously until such items are addressed. Updated information may change the results and conclusions of this research.

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Summary

Sustainable aviation fuels (SAF) are seen as an important technology to decarbonise aviation and thus to meet climate targets. This report explores the supply of SAF by summarising the potential of feedstocks for SAF production in the Netherlands based on RED II sustainability requirements, in order to identify the most relevant opportunities for the Netherlands. To this end, literature was reviewed to quantify the availability of feedstocks for biofuels and e-fuels, after which an overview of total potential for SAF production based on feedstock availability was computed. This overview is visualised in Figure 1.

The key take-aways of this research are:
- The availability of feedstocks for biofuels in the Netherlands in 2050 is expected to be far lower than the range of demand for aviation. Even this number of 35 PJ may be too optimistic, as other industries than aviation may claim these freely available and additional resources.
- Based upon a proportionate fraction of the excess biomass that France, Sweden, Germany and Ukraine are expected to have in 2050, it seems that trade within the EU could cover the national deficit. However, sustainability of transporting feedstocks, dependency on other countries for fuel and willingness of those countries to trade must be taken into account. Therefore, this option is less desirable than national production, but can be fallen back upon if necessary to achieve climate targets.
- If the forecast excess renewable electricity available in the Netherlands in 2050 is completely allocated to production of synthetic fuels for aviation, projected demands could largely be met. This holds for production of synthetic fuels both via direct air capture and recycled carbon. If and to what extent excess renewable electricity will be available to aviation is currently unclear. If this is substantially lower than 100%, it might not be possible to cover the aviation fuel demand.
- In order to obtain a reliable forecast of the availability of SAF for aviation, future allocation of renewable energy, specifically biomass and renewable electricity, must be addressed. Until this is done, results must be interpreted cautiously.

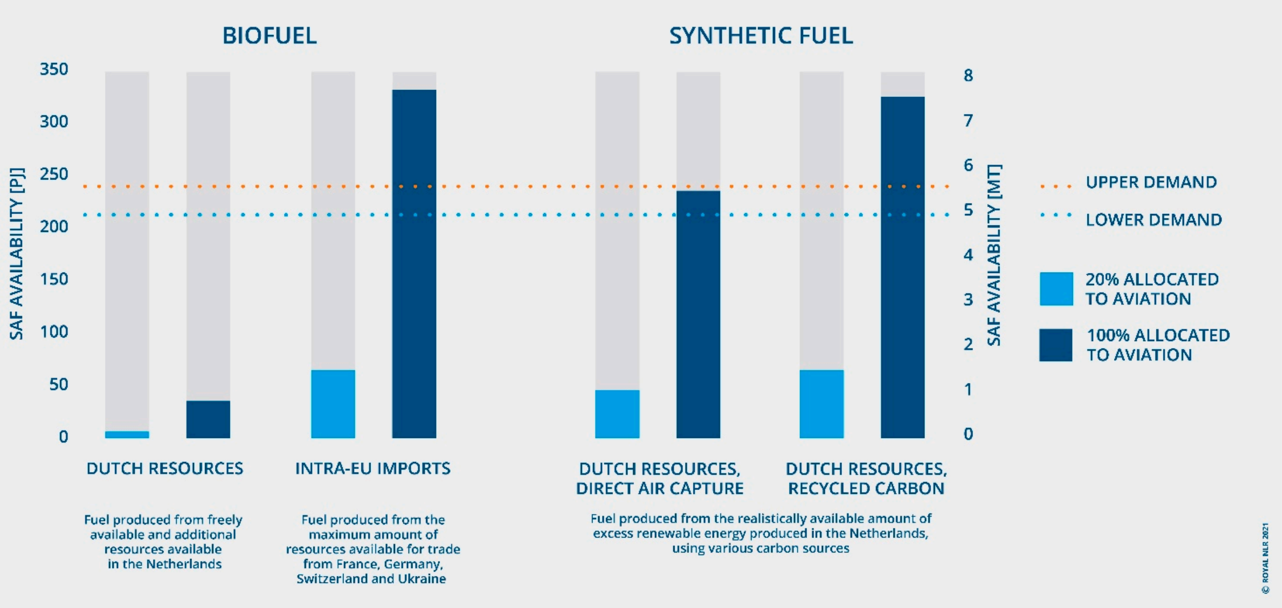

Figure 1: SAF potential for the Netherlands in 2050 based on feedstock availability

Contents

Abbreviations

ACRONYM	DESCRIPTION
AE	Alkaline Electrolysis
AEM	Anion Exchange Membrane
ATAG	Air Transport Action Group
CCS	Carbon Capture & Storage
CCU	Carbon Capture & Use
CHP	Combined Heat & Power
DAC	Direct Air Capture
EC	European Commission
ETS	Emissions Trading System
EU	European Union
GW	Gigawatt
IAS	International Aviation and Shipping
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre (EU)
MSW	Municipal Solid Waste
Mt	Megatonne (1000 tonnes; 1 million kilogrammes)
NDC	Nationally Determined Contribution (Paris Agreement)
NLR	Royal Netherlands Aerospace Centre
PEM	Proton Exchange Membrane
PJ	Petajoule
PtL	Power to Liquid
RCF	Recycled Carbon Fuel
RED II	Renewable Energy Directive II
SAF	Sustainable Aviation Fuel
SOE	Solid Oxide Electrolysis
SRC	Short Rotation Coppice
TWh	Terawatt-hour (1 TWh = 3.6 PJ; 1 TW = 1000 GW)
UCO	Used Cooking Oil

1 Introduction

Reducing aviation's carbon footprint is critical to achieve global emission reductions as outlined in the Paris Climate Agreement and European emission reductions as outlined in the European Green Deal (ICAO, 2019; European Commission, 2020). Therefore, the aerospace industry is exploring various measures to reduce emissions. Whilst there is a great public interest in radical innovations in propulsion technology such as (hybrid-)electric and hydrogen based propulsion, for the short term – and probably also for long(er) haul flights in the long term – aviation will be dependent on hydrocarbons. Using sustainable aviation fuels (SAF), net carbon emissions can be substantially reduced, while aviation can continue to rely (indefinitely, or for a transition period) on hydrocarbons.

SAF continues to receive substantial interest from both public and private parties in the Netherlands. In February 2021 the Dutch Ministry of Infrastructure and Water Management hosted a High Level Conference on Synthetic Sustainable Aviation Fuels to accelerate the dialogue on Synthetic SAF and create favourable conditions for the production and deployment of synthetic fuels. This conference highlights the importance given to SAF in the policy framework to lower aviation emissions. In a similar context The Netherlands has set a 14% blend-in target for 2030 as part of the *Luchtvaartnota* or Civil Aviation Policy Memorandum. The latest knowledge on SAF and discussions on the policy framework take place in the "Werkgroep Duurzame Brandstoffen" also hosted by the Ministry of Infrastructure and Water Management. Furthermore, The Netherlands has numerous companies which are involved in SAF-production – both at commercial or pilot scale[1]. Fitting with that interest, this report intends to contribute to the knowledge building and exchange about the potential for SAF production in the Netherlands. The results can subsequently be used to guide discussions, determine further research topics and inform scenarios to be analysed.

The remainder of this introductory chapter presents the formal research objective, scope, study approach and report structure.

> **A WORD ON COVID-19 AND PROJECT TIMELINE**
> This project was initiated and largely completed before the full and lasting impact of COVID-19 on the aviation sector became clear. This means that projections, for example on future demand for aviation or future energy demand or supply, do not include these impacts. As the pandemic and related economic crisis are however foreseen to be of a rather temporary nature compared to the timelines of this study (looking towards 2050) and such timelines inherently come with uncertainty, the relevance of the results and conclusions presented here is considered to be largely unaffected.
>
> Furthermore, as the majority of the work was conducted halfway through 2020, minor developments during the intermediate period may not be (fully) reflected in this work. A February 2021 review and update prior to finalization focused on the incorporation of stakeholder feedback and did not include a systematic review of newly published literature.

1.1 Objective

The primary objective of this research is to identify the most promising feedstocks for the production of large quantities of SAF in the Netherlands towards 2050, based on availability and sustainability of feedstocks sourced from the Netherlands or Europe for the production of SAF in the Netherlands in the 2050 timeframe.

A sub-objective is to identify the areas in which additional research is needed to make informed policy decisions.

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[1] Developments in the Netherlands are discussed in more detail in Section 2.2.

1.2 Scope

The research has been scoped in the following manner:

- Only drop-in SAF was considered.
- Primary interest went out to resources available in the Netherlands. In case preliminary results showed these to be limited, EU resources are taken into account as well. Worldwide resources were not considered.
- In terms of feedstocks, only biomass, renewable electricity, hydrogen and non-organic carbon (including recycled carbon) were considered. Only feedstock types that are suitable for the production of SAF were taken into account.
- With respect to the allocation of (freely) available feedstock for production of SAF (i.e., use by the aviation sector), two scenarios have been considered (100% and 20%). The division of sustainable feedstocks over different sectors is out of scope.
- Sustainability requirements are taken from the RED II framework.
- In comparing availability and demand, possible economic impacts by the use of SAF (such as ticket price increases) have not been taken into account.

1.3 Approach

The following approach was applied:

- Literature was reviewed in order to describe the availability of all relevant feedstocks.
- A comparison was made between feedstocks based on a pre-defined set of criteria.
- Feedback was collected from the Werkgroep Duurzame Brandstoffen.

1.4 Structure

The report is structured as follows. Chapter 2 discusses relevant context, for example providing technical and policy background to SAF and discussing anticipated SAF demand. Chapters 3 and 4 form the main body of this report, describing feedstock and resource availability for respectively biofuels and e-fuels. Chapter 5 provides an overview of SAF availability and relates it to demand estimates for 2050. Conclusions and recommendations, last, are presented in Chapter 6.

2 Context

This chapter presents the context of this research. Starting with a short background on SAF (Section 2.1), it discusses developments in the Netherlands (Section 2.2) and the EU Renewable Energy Directive which forms a main piece of legislature guiding the development of SAF (Section 2.3). Section 2.4 pays attention to anticipated demand for SAF, depending on the development of the aviation sector over the coming decades. Last, Section 2.5 discusses the allocation of renewable resources to various sectors.

2.1 Background to SAF

As indicated in Chapter 1, the use of SAF is seen as an important way of substantially reducing carbon dioxide emissions form commercial aviation. IATA defines SAF as "fuel for aviation with an alternative feedstock to crude oil. In this case non-conventional or advanced fuels, and includes any materials or substances that can be used as fuels, other than conventional, fossil-sources (such as oil, coal, and natural gas). It is also processed to jet fuel in an alternative manner" (IATA, 2020, p. 1). Sustainability criteria are used to assess the sustainability of the fuel. In Europe, sustainability of alternative fuels is largely defined in the RED II framework (European Commission, 2019).

SAF can be drop-in, which means that its chemical properties are so close to those of fossil kerosene that it can be used mixed with fossil kerosene in conventional jet engines. Alternatively, SAF can be non-drop-in, meaning the chemical composition differs significantly from that of fossil kerosene and adaptions to the engine and/or aircraft are needed to use it[2]. Carbon emissions are reduced when SAF is combusted in comparison to fossil hydrocarbons because SAF has taken up atmospheric carbon during its production. SAFs can be roughly split into two categories: biofuels, primarily produced from organic materials which have taken up carbon dioxide during their lifetime, and synthetic fuels, produced from inorganic carbon dioxide (CO_2) and hydrogen (H_2). Over the entire life cycle, carbon reductions from using SAF are estimated to be upwards of 65% (cf. Table 1).

In 2009, ATAG and IATA both predicted that in 2020, 10-15% of all aviation fuel consumed would be SAF (ATAG, 2009; IATA, 2008). At present (mid-2020), SAF consumption actually only accounts for < 1% of global aviation fuel demand (IATA, 2020). This is caused by both supply issues (unavailability of large volumes) and demand issues (airlines are unwilling to cover the price premium for SAF and maintain current ticket prices), which strengthen each other in a vicious circle (Dichter, Henderson, Riedel, & Riefer, 2020). Currently, SAF production is almost entirely consists of hydro-processed esters and fatty acids (HEFA), as that pathway is the only one used for commercial production. The current limited availability of used cooking oil (UCO) feedstocks limits the upscaling of current bio-kerosene facilities.

This report explores the supply aspect by summarising the potential of feedstocks for SAF production based on RED II sustainability requirements, in order to identify the most relevant opportunities for the Netherlands. As indicated in Section 1.2, this research is limited to drop-in SAF.

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[2] An example that has been receiving substantial interest in the aviation context is the use of (liquid) hydrogen, studied in e.g. McKinsey & Company (2020) and Van der Sman et al. (2021).

2.2 Developments in the Netherlands

In the Netherlands several parties are active in the development of SAF. Representatives from the industry, government and knowledge institutes come together periodically in the “Werkgroep Duurzame Brandstoffen”, hosted by the Ministry of Infrastructure and Water Management. This working group has also set up an action programme (Actieprogramma Duurzame brandstoffen).

In addition to more fundamental research carried out at e.g. Wageningen University & Research and Delft University of Technology, a number of commercial companies in the Netherlands are active in or working towards commercial availability of SAF. SkyNRG, the global market leader in SAF, is based in Amsterdam and is involved in several SAF pilots. Most notably, SkyNRG aims to build a first SAF production facility in the Netherlands, DSL-01, which was financed via corporate commitments to buy SAF from 2022. Shell supports this project. Another energy company active in SAF is Neste, a Finnish company which has had a biorefinery in Rotterdam since 2011 and is looking to expand its production of aviation fuel. In parallel to these bio-based activities, at Rotterdam The Hague Airport a pilot facility for synthetic kerosene based on Direct Air Capture is in the planning. Very recently a start-up company SynKero has been launched, which aims to develop a synthetic kerosene facility in the Port of Amsterdam based on renewable hydrogen and CO_2 from either point sources or directly from the air.

2.3 Renewable Energy Directive

The Renewable Energy Directive (RED) and its recast towards 2030 (called RED II) outlines a European approach to renewables, including biofuels and synthetic fuels (EP, 2018). The RED II defines the following categories of SAF:

- Sustainable biofuels which shall meet the EUs sustainability criteria:
    - Crop-based biofuels
    - Waste-based biofuels
    - Advanced biofuels
- Renewable fuels of non-biological origins
- Recycled carbon fuels

The RED II also contains sustainability criteria for SAFs (EC, 2019; EC, 2020). These criteria include a minimum level of GHG savings over the life cycle of the fuel. The threshold depends on the start date of the plant and the type of fuel. An overview of the GHG savings requirements is given in Table 1.

Table 1: GHG savings thresholds according to RED II framework

Plant operation start date	Transport biofuels	Transport renewable fuels of non-biological origin	Electricity, heating and cooling
Before October 2015	50%	-	-
After October 2015	60%	-	-
After January 2021	65%	70%	70%
After January 2026	65%	70%	80%

The RED also considers the impact of fuel production on areas of high carbon stock such as wetland, forest and peat land and the impact on land with high biodiversity. To limit the risk of (indirect) land use change (ILUC) the RED II frameworks sets a cap on high ILUC-risk fuels. This cap will gradually decrease to zero towards 2030. These fuels are assessed based on the feedstocks used. The RED uses a list of feedstocks which are specified in Annex IX of the directive and divided in Part A for advanced feedstocks and Part B for capped feedstocks.

2.4 Demand for SAF

Although numerous factors – new technology and fleet replacement, more efficient air traffic management, and operational improvements – contribute to reducing CO_2 emissions of commercial aviation, worldwide growth more than offsets these improvements. The fact that drop-in SAF can be used in existing aircraft and using existing supply chains while at the same time drastically cutting carbon emissions results in a notable demand for SAF[3].

Uitbeijerse (2020) has estimated the amount of CO_2 emitted by commercial flights departing from the main Dutch airports (Amsterdam Airport Schiphol, Eindhoven Airport, Rotterdam The Hague Airport, Maastricht Aachen Airport and Groningen Airport Eelde) for 2030 and 2050. These estimates are based on the WLO-scenario's, developed in 2015 (CPB / PBL, 2015) and updated in 2019 (Significance & To70, 2019). In working towards estimating the total CO_2 emission, the total energy use is computed. Depending on the scenario (high or low), higher or lower energy efficiency improvements are modelled. Increases in energy efficiency are a result of improvements in aircraft and engine technology as well as more efficient aircraft operations, including seat densification and higher load factors. Assumed efficiency improvement figures and the resulting estimated energy demand is shown in Table 2. More details are provided by Uitbeijerse (2020).

Table 2: Estimated energy demand for commercial flights departing main Dutch airports and assumed efficiency improvement (Uitbeijerse, 2020)

Year	Efficiency improvement [% p.a.]		Energy demand [PJ]	
	Low scenario	High scenario	Low scenario	High scenario
2017 (base year)			169	
2030	0.6	1.5	201	220
2050			214	241

It is emphasised that these figures are scenario-based estimates, subject to uncertainty. As also the difference in efficiency improvement figures shows, especially 2050-outputs might differ. Nevertheless, estimates are in line with the author's own analyses[4], and in range of estimates by den Ouden et al. (2020, p. 74)[5].

Efficiency improvement figures substantially influence the above outcomes. With zero efficiency improvement, energy demand would range between 217 and 237 PJ for 2030 and between 349 and 392 PJ for 2050. More aggressive energy efficiency improvements, on the other hand, result in lower energy demand estimates. A 1.75% p.a. improvement, based on the "Smart and Sustainable" action plan presented in 2018[6], would for example require 173 to 190 PJ of energy in 2030 and 197 to 222 PJ in 2050. If longer-term efficiency improvements would increase beyond that, as suggested by Van der Sman et al. (2021), the 2050-figures might further reduce.

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[3] Although out of the scope of this report, a similar demand for sustainable fuels is seen from the international shipping sector.

[4] Data from CBS (2021) shows international aviation departing from the Netherlands bunkered 147.8 PJ (3396 million kg) in 2013. In the WLO-scenarios developed by CBS and PBL in 2015, the passenger aviation volume ("vervoersvolume passagiers") is estimated to increase from index 100 in 2013 to 155 to 163 in 2030 and to 210 to 243 in 2050 (CPB / PBL, 2015). This is equivalent to an annual growth of 2.6 to 2.9% up to 2030 and between 2.0 and 2.4% up to 2050. Applying these growth factors to the 2013 kerosene bunkers, demand for 2030 would be between 229 and 241 PJ and demand for 2050 would range from 310 to 359 PJ. With a 1% efficiency improvement, an assumption based on Kharina & Rutherford (2015) and an analysis of "upcoming aircraft" listed in (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), reduces the WLO-based demand for fuels to 193 and 203 PJ for 2030 and 214 to 248 PJ for 2050[4].

[5] Den Ouden et al. (2020) assume aviation sector growth of -1, 0, 1 or 2% per year between 2015 and 2050, yielding energy demand estimates between 125 and 315 PJ.

[6] This action plan estimates a reduction in CO_2 emissions compared to the lower WLO scenario for 2030 of 35%. Approximately 25% of this reduction is to be delivered by the use of SAF, leaving about 26% of efficiency improvements. Over the 17-year difference between 2030 (the horizon year) and 2013 (the index year used in the WLO-scenario), this is equivalent to an annual improvement of 1.76%.

The above analyses concern total energy demand for aviation and do not take into account possible alternative energy carriers, such as fully or partially electric aircraft, or aircraft powered by hydrogen (either used in a fuel cell or combusted in a gas turbine). Their implementation will also affect the demand for drop-in sustainable aviation fuel. For 2030, this impact is estimated to be 1% of the energy demand, to grow to 15% in 2050[7].

Given this more innovative technology pathway, a third scenario is added to those presented in Table 2. For 2050, this yields three demand estimates for drop-in SAF, presented in Table 3. This includes total energy demand estimates (expressed in PJ) and demand estimates for drop-in SAF (expressed in megatonne, using 43.5 MJ/kg). These scenarios do not take into account the effects of possible cost and price changes due to the (increased) use of SAF on demand.

Table 3: Energy and drop-in SAF demand scenarios for 2050

Scenario	Demand growth	Technology development and efficiency improvement	Energy demand [PJ]	Drop-in SAF demand [Mt]
WLO Low	Low	Lower; 0.6% efficiency improvement per year.	214	4.9
WLO High	High	Higher; 1.5% efficiency improvement per year.	241	5.5
High-Tech	High	Highest; 1.75% efficiency improvement per year. 15% of energy demand fulfilled by non-hydrocarbons.	222	4.3

2.5 Allocation of renewable resources

Aviation is not the only sector which needs to transition to renewable energy sources. In the coming years, policy makers at a national, European and global level must decide whether it is desirable to allocate renewable resources to certain industries, or whether it is preferable to leave the division of renewable resources to market forces. As that division is currently far from clear, this report does not take into account which percentage of renewable resources will be available for aviation. That means that this report assumes that all available resources[8] are available to the aviation sector.

That, however, is an assumption easily challenged. The aviation industry will very likely have to share feedstocks with other industries. This must be taken into account when interpreting the findings of this research, as not to overestimate the future potential of SAF and not to draw conclusions that are overly optimistic. In order to illustrate the influence of this allocation problem, the following box provides examples of a variety of ways resources might be divided. It is stressed these examples are prepared by the authors of this study and have not been based in current policy discussions. A market-driven allocation was out of the scope of this study, and therefore is not included.

> **ILLUSTRATIVE EXAMPLES OF ALLOCATION OF RENEWABLE RESOURCES TO AVIATION**
> This box provides a number of examples on the possible (policy-driven) allocation of renewable resources to aviation. It is intended to show a variety of possible shares, illustrating the impact this allocation problem has on the overall aviation sustainability challenge.

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[7] Van der Sman et al. (2021) anticipate the introduction of a hydrogen-powered aircraft for intra-European routes below 2000 kilometres by 2035, such that it has a 2/3rd market share in that market segment. Estimates of CO_2 emissions per flight by internal NLR-analyses support this assumption, as a similar segment of flights (below 2000 kilometres, from EHAM to E*** and L***) was found to contribute approximately 16% of CO_2 emissions.

[8] In case of Chapter 3, this concerns available feedstock for the production of aviation biofuels. In Chapter 4, this concerns excess renewable electricity (additional to anticipated use) and inorganic carbon.

A first option discussed here is based on decarbonisation potential and alternatives across sectors. The Energy Transitions Committee (ETC, 2018) has identified aviation as a 'hard to abate' sector. The role for electrically- or even hydrogen-powered aviation is foreseen to be limited to shorter distance flights[9], with long distance air travel relying on drop-in sustainable aviation fuels. Discussing the allocation of biomass across different hard to abate sectors, the ETC (2018, p. 25) notes "the highest priority sector appears to be aviation", supporting the assumption of large biomass availability for SAF-production. On the other hand, electrification and the use of renewable hydrogen (also produced from renewable electricity, as further discussed in Section 4.1.2.1) are estimated to play a pronounced role in other sectors, such as heavy-duty road transport and steel production as well. Depending on how such needs are factored in to estimates for the demand for electricity in 2050 (discussed in Section 4.2.3), not all renewable electricity identified as 'excess' in this study, is available for aviation.

Another option would be to equally split the amount of available renewable energy for transport over aviation, shipping and road transport. This is an approach adopted by Van der Sman et al. (2021) regarding the allocation of hydrogen. Regarding hydrogen specifically, Trinomics (2020) has estimated that for 2030, between 11 and 35% of the hydrogen for transport (between 30 and 43% of the total amount of hydrogen available) will be used by aviation.

A third option – or: group of options – is more data-driven: allocate future energy shares based on their current share or, for example, based on the amount of jobs or economic value an energy-consuming activity brings. Starting with the former, total final energy consumption in 2019 (preliminary data, CBS, 2020) was 1.854,9 PJ. Adding to this the sale of bunker fuels (preliminary data, CBS, 2021) yields a grand total of 2.493,5 PJ, of which less than 7% (166,3 PJ for bunkers and 1.6 PJ for domestic flights) is used for aviation. For the latter, Faber & van Wijngaarden (2019) cite two studies that estimate the economic contribution of the aviation sector to be between 300.000 jobs and 23.5 billion (2016, including direct, indirect and induced effects) and 370.050 jobs and 27 billion (2015, also including catalytic effects). Given total employment and GDP figures (CBS, 2020; CBS, 2020), this yields a range of 3.3% to 4.2% in terms of people employed and 3.3% to 3.9% in terms of GDP. Only looking at direct effects, these numbers and shares will decrease.

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[9] For electrically-powered aviation, this view is still in line with current thinking. For hydrogen-powered aviation, expectations have increased, for example due to the publication of a report on the topic by McKinsey & Company (2020)..

3 Feedstocks for biofuels

Biofuels are made from feedstocks derived from organic material, called biomass. The organic material can originate from multiple sources such as trees, plants and waste. This section starts with a description of the types of biomass feedstocks, followed by the availability of these feedstocks in the Netherlands and in the EU. This information is then used to identify the feedstocks with the highest potential for the production of bio-kerosene in the Netherlands.

3.1 Biomass classification

Biomass feedstocks can be classified in multiple ways based on sector, category and type. Differences in classification make it difficult to directly compare various literature sources. Therefore, a brief explanation is given of the most common classifications of biomass including the respective categories and types. This short review does not intend to comment on correctness or suitability of different classification schemes.

Multiple sources make a distinction between the agricultural sector, the forestry sector and the waste sector (Ruiz, et al., 2015; Leguijt, et al., 2020). Some studies however do not consider the division between sectors and directly divide the biomass in categories (Bentsen & Felby, 2012). This often leads to the following classification: forest biomass, agricultural residues, energy crops and already processed biomass. For this report the division between sectors will be used as the first classification step consistent with publications used for the Dutch and EU biomass availability analysis.

The JRC report classifies the biomass based on sector type followed by a further specification by category and then by type. (Ruiz, et al., 2015) It should be noted that this report defines a separate category within the agriculture sector for solid residues such as straw. This leads to the classification presented in Table 4.

Table 4: Biomass classification according to JRC report (Ruiz, et al., 2015)

Sector	Category	Type
Agriculture	Energy crops	Sugar, starch & oil crops
		Dedicated perennials- woody/ lignocellulosic biomass
		Energy maize / silage
	Primary agricultural residues	Dry manure
		Liquid/wet manure
	Secondary agricultural residues	Olive pits
	Solid agricultural residues	Pruning and straw/stubble
Forestry	Stemwood production	Stemwood
		Additionally harvestable stemwood (woodchips and pellets)
	Primary forestry residues	Logging residues
		Landscape care (potentials outside agricultural permanent cropland)
	Secondary forestry residues	Woodchips, pellets, sawdust and black liquor
Waste	Primary residues	Biodegradable waste such as Public greens (road side verges)

Sector	Category	Type
	Tertiary residues	Biodegradable waste such as Municipal Solid Waste (renewables), other waste (abandoned grass cuttings, vegetable waste, shells/husks)
		Other waste such as Sewage sludge, paper and cardboard waste, dredging spoils

In the recently published CE Delft report, however, waste is not considered as a separate sector but it is included in the agricultural and forestry sectors as shown in Table 5 (Leguijt, et al., 2020). Within these sectors the report classifies waste as tertiary residue streams of the agricultural and forestry sector. Energy crops are, furthermore, classified as "production" within the agriculture sector.

Table 5: Biomass classification according to CE Delft report (Leguijt, et al., 2020)

Sector	Category	Type
Agriculture	Production	Corn, sugar cane, beet, soy, canola, grass
		Woody crops (including willow), grassy crops
	Primary residues	Beet leaves, straw, manure
	Secondary residues	Beet pulp, offal, legume husks
	Tertiary residues	Biodegradable waste, WWTP sludge, discarded textile, organic fraction of household waste, used fats and oils, landfill gas
Forestry	Production	Saw wood
	Primary residues	Thinning wood, branch and top wood, leaves, bark
	Secondary residues	Sawdust
	Tertiary residues	Consumer waste wood, industrial waste wood, waste paper and cardboard

3.1.1 Agriculture biomass

Biomass from agriculture can be divided in the following categories: energy crops, primary and secondary residues.

Energy crops

Plants convert the energy of the sun by using photosynthesis into energy rich materials. After harvesting, the energy stored in plants can be converted to biofuel, heat and power. Energy crops are grown exclusively or primarily for the purpose of producing biomass for energy. The concept of growing dedicated crops for the production of biofuel has recently expanded and reached commercial scales. These practices can, however, incur significant environmental impact, due to land use change and the competition with food production. These biofuels are often called "first generation" biofuels and are produced from crops such as grain, sugar and oil-seed crops.

In this analysis the focus lies on advanced feedstocks that have lower environmental impact and meet higher sustainability standards. The energy crops considered in this analysis therefore consist of non-food lignocellulosic energy crops. The name refers to the higher content of cellulose and lignin present in the stems and leaves. These energy crops are often categorized in two types: perennial herbaceous crops and woody crops known as short rotation coppice (SRC). Examples of non-food lignocellulosic energy crops are given in Table 6.

Table 6: Examples of the two types of non-food lignocellulosic energy crops

Type	Examples
Perennial herbaceous crops	Miscanthus, switchgrass, reed canary grass, giant reed, perennial rye grass etc.
Short rotation coppice	Willow, poplar, eucalyptus, paulownia etc.

Residues

Agricultural residues are often categorized in primary and secondary agricultural residues. Both types can be used for energy production. In addition, the JRC publication defines a separate category for solid residues like straw. In most publications however, straw is considered a primary agricultural residue. Agricultural residues like straw, leaves and stalks mainly originate from the European cereal production, more specifically from the production of wheat, maize, barley and rye (Bentsen & Felby, 2012). Primary residues are the result of primary agricultural operations (such as straw from grass species), whereas secondary agricultural residues are produced during the processing of crops into food or other products (Khawaja & Janssen, 2014).

Wastes

Tertiary agricultural residues are elaborated in Section 3.1.3. This section considers all waste streams including those from agriculture, such as vegetal, food and household wastes.

3.1.2 Forestry biomass

Forestry biomass includes wood and harvest residues. Currently, forestry biomass accounts for around half of the EU's total renewable energy consumption (Khawaja & Janssen, 2014). Up to now, forestry biomass has mainly been used for material demand, it can however also be used for energy purposes. In the future, the use of forestry biomass for energy is expected to increase and exceed the demand for material use. Currently, the most efficient pathways to transform forestry biomass into energy are heat production and CHP installations (Khawaja & Janssen, 2014). Transporting biofuels or pellets is more efficient than transporting large volumes of bulky, moist wood (Khawaja & Janssen, 2014). Therefore transportation of feedstock should be done only over short distances to increase the efficiency of the pathway.

The expansion of production of forestry biomass is linked to the expansion of forest area and the amount of collected forestry residues. The portion of residues that can be extracted is constrained by factors such as soil carbon content, nutrient flows, water holding capacity and biodiversity. To significantly expand the wood supply the s2biom project suggests establishing short rotation coppice in an agricultural setting. However, also energy cropping should take into account land use and other sustainability criteria.

Tertiary forestry residues are elaborated in Section 3.1.3. This section considers all waste streams including those from forestry, such as wooden packaging, sawdust, wood from the production of pulp and paper and wood from the construction and demolition of buildings.

3.1.3 Waste

Wastes can be classified in multiple categories. Wastes can be considered a separate sector or they can be included in the agricultural and forestry sector as tertiary rest streams. Waste streams can be classified according to the division shown in Table 7, aligned with the EWC-Stat categories (eurostat, 2010). These categories have been defined by the EU in order to compare data from Member States.

Table 7: Types of waste including respective sources (eurostat, 2010)

	Type	Source
Paper and cardboard wastes	Fibre, filler and coating rejects from pulp, paper and cardboard production	Separate collection, mechanical treatment of waste and pulp, and paper and cardboard production and processing
Wood wastes	Wooden packaging, sawdust, shavings, cuttings, waste bark, cork and wood from the production of pulp and paper; wood from the construction and demolition of buildings; and separately collected wood waste.	Wood processing, the pulp and paper industry and the demolition of buildings
Animal and mixed food wastes	Sludges from washing and cleaning; separately collected biodegradable kitchen and canteen waste, and edible oils and fats	Food preparation and products
Vegetal wastes	Sludges from washing and cleaning, materials unsuitable for consumption and green wastes	Food and beverage production, and from agriculture, horticulture and forestry
Household and similar wastes	Mixed municipal waste, bulky waste, street-cleaning waste like packaging, kitchen waste, and household equipment except separately collected fractions	Streams originate mainly from households but can also be generated by all sectors in canteens and offices as consumption residues
Sorting residues mechanical	Sorting processes for waste; combustible waste (refuse derived fuel); and non-composted fractions of biodegradable waste	Waste treatment and separate collection
Common sludges	Waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing	Households and industrial branches with organic waste water

3.2 NL resources

The availability of national biomass resources is elaborated in this section. Currently, the biofuel market is dominated by UCO and animal fat feedstocks which are often not locally resourced and which will be capped under the RED II. This section therefore explores all available biomass resources in the Netherlands for the production of biofuels for aviation.

Methodology

The availability of feedstocks for the production of biofuels for aviation has been analysed based on two recent publications from CE Delft and ICCT. These publications analyse the amount of national resources in relation to the renewable energy targets or sub-targets. Scope and objective of these studies are different, but common elements haven been identified that can be used to analyse the biomass potential for aviation. The ICCT publication “Assessing the potential advanced alternative fuel volumes in the Netherlands in 2030” focuses on feedstocks eligible under the

RED II framework for the road transport sector. CE Delft report "Bio-scope" analyses the biomass potential for various sectors of the economy including aviation.

Assessing the potential advanced alternative fuel volumes in the Netherlands in 2030 - ICCT (2020)

According to ICCT, the national feedstock potential ranges from 0.9 – 1.5 million tonnes in 2030 for the production of biofuels for transport as shown in Table 8. This range can be converted to PJ per year taking a conversion factor of 15 PJ per million tonnes of biomass input, resulting in a range between 14 and 22 PJ per year in 2030. Agricultural and forestry residues are considered unavailable as these feedstocks are already used in other sectors and further harvesting is constrained by levels of erosion and soil nutrient loss. Based on these feedstocks, the study estimates that 8 PJ of biofuels per year could be produced with medium (€1 / litre) and high (€2 / litre) policy support mechanisms for the road transport sector. These support mechanisms are based on biodiesel and bioethanol prices.

Table 8: National biomass resources according to ICCT for the production of biofuels for transport and estimates for the production of biofuels based on medium and high policy support incentives in 2030 (Pavlenko & Searle, 2020)

Feedstock type	Tonnes (2030)	Estimate in PJ/year (2030)[10]	Biofuel amount in PJ/year (2030)
Agricultural residues	0[11]	0	0
Forestry residues	0[12]	0	0
MSW	600000	9	2
UCO	141000	2	3
Energy crops	192000 – 709300[13]	3 – 10	3
Total	**933000 – 1450000**	**14 – 22**	**8**

Bio-scope - CE Delft (2020)

National biomass resources are estimated between 342 – 390 PJ per year in 2030 and between 372 – 454 PJ per year in 2050. A large portion of these feedstocks come from agricultural residues which are already used for cattle breeding. In the context of this report the "freely available and additional" resources give a better estimate of the untapped potential which could be used in aviation, as shown in Table 9. The amount of untapped feedstocks in 2030 is estimated around 5 PJ per year as most feedstocks are already being used. For 2050, the unused national biomass resources are estimated to increase and could reach around 60 PJ per year.

Table 9: National "freely available and additional" biomass resources according to CE Delft in 2030 and 2050 (Leguijt, et al., 2020, Table 45, p. 126)

Type of feedstock	2030 amount in PJ/year	2050 amount in PJ/year
Potential energy crops	0	25
Forestry production	5	5
Primary agricultural residues	0	13
Secondary agricultural residues	0	10
Secondary forestry residues	0	5
Tertiary residues (wastes)	0	5
Total	**5**	**63**

CE Delft estimates that the use of biomass for energy production (such as biofuels for transport) will increase drastically by 77% in 2030 and 85% in 2050 (Leguijt, et al., 2020). The largest contribution in this increasing amount would come from bunker fuels (81%) for marine and aviation. However, bunker fuels for aviation would represent 10% of the bunker fuel amount (Leguijt, et al., 2020). Based on this division between sectors, 81% the 63 PJ in 2050

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[10] Estimate based on conversion factor for biomass of 15 PJ/ million tonnes

[11] Agricultural residues in the Netherlands are already used in other industries and therefore the unused potential is set to zero.

[12] Forestry residues in the Netherlands are already used in other industries and therefore the unused potential is set to zero.

[13] Based on 41,000 hectares with yields ranging from 4.7 to 17.3 dry tonnes per hectare

could be used for the production of bunker fuels resulting in 51 PJ of biomass feedstocks. Of these 51 PJ, only 10% would be used for aviation resulting in 5 PJ of national feedstocks for the production of aviation biofuel with national resources.

Common elements and conclusions

ICCT and CE Delft highlight that biomass resources in the Netherlands are very limited and most likely not sufficient to meet future demand (if all sector of the economy are taken into account). The Netherlands has a much lower availability of unused agricultural residues and a much lower energy crop potential compared to other EU countries. These two factors have been identified as the main reasons for the limited biomass potential.

“Freely available and additional resources” are estimated around 60 PJ per year in 2050. A portion of these resources may be used to produce biofuels specifically for aviation. In 2030, biomass resources for all transport modes are estimated between 14 and 22 PJ per year according to ICCT. CE Delft, however, identifies only 5 PJ per year of “freely available” resources in 2030.

As mentioned in the introduction, the division of feedstocks between sectors is out of the scope. If other sectors would be taken into account, the availability of national resources for aviation will probably represent a portion of the indicated national biomass resources. Aviation has to compete for biomass resources with the road transport sector, as indicated by the ICCT study which focused specifically on road transport. In the 2030 timeframe the road sector is expected to increasingly electrify to meet the Dutch renewable energy targets, but a large portion of the cars will still rely of liquid fuels. This shows that electrification of the road sector may enable a larger portion of biofuels to be used in aviation. As shown by the CE Delft study, also shipping will rely on biomass resources in the 2050 timeframe. The Bio-scope report expects a large portion of biomass to be used for the production of bunker fuels, but estimates a small amount for aviation compared to shipping. Other untapped national resources such as flue gasses and renewable electricity for the production of power to liquid fuels and hydrogen are analysed in Chapter 4.

Given the limited availability of national biomass resources, ICCT and CE Delft consider importing feedstocks from the EU and worldwide. The next section of this report considers the import of sustainable biomass feedstocks from other EU countries. These biomass feedstocks may be imported if these countries cannot scale-up their own production in time or simply have a lower demand. Sustainability of transporting large amount of feedstocks should however be taken into account combined with added cost and loss in efficiency.

3.3 EU resources

This section addresses the availability of resources from the European Union and neighbouring countries.

3.3.1 Demand and availability of feedstocks

Methodology

The analysis has been made on the basis of three publications: IRENA Remap, BioSustain Final Report, and S2BIOM report. BioSustain “Sustainable and optimal use of biomass for energy in the EU beyond 2020” is a project funded by the European Commission which aimed to develop plausible EU bioenergy supply and demand scenarios for 2030 and assess the environmental and socio-economic impacts of possible future EU action to ensure bioenergy sustainability post-2020. The International Renewable Energy Agency (IRENA) published the working paper “Global Bioenergy

Supply and Demand Projections" in 2014 to address a number of crucial questions in view of biomass' large demand potential such as biomass availability, as well as the uncertainties concerning supply in a sustainable, affordable way and how this might be ensured. The main objective of the S2Biom project was to support the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies, roadmaps and updated harmonized datasets at local, regional, national and pan European level for EU28, Western Balkans, Moldova, Turkey and Ukraine.

Besides these publications, a series of papers have been analysed in other to compliment the overview of resource availability in the countries with highest supply potential inside Europe. These will be mentioned later on in the subsection 'Trade Possibilities for the Netherlands'.

Overall availability and division between sectors

According to BioSustain, in 2017 bioenergy was the primary source of renewable energy. In the next 10 years bioenergy demand is expected to keep growing, and biomass will be a key resource for meeting the European renewable energy targets. The IRENA Remap is consistent with the estimates of BioSustain in that the largest demand for biomass comes from the heating sector, followed by electricity generation and transport fuel. According to IRENA's report, the largest growth rate originated from the transport sector, reaching an annual growth rate of 5.4% in 1990 – 2000 and even a higher annual rate of 19.2% over the period 2000 – 2010. In 2030, IRENA Remap estimates that 31000 PJ will be used for the generation of biofuels for transportation, being 63% dedicated to conventional biofuels and 37% for advanced biofuels[14].

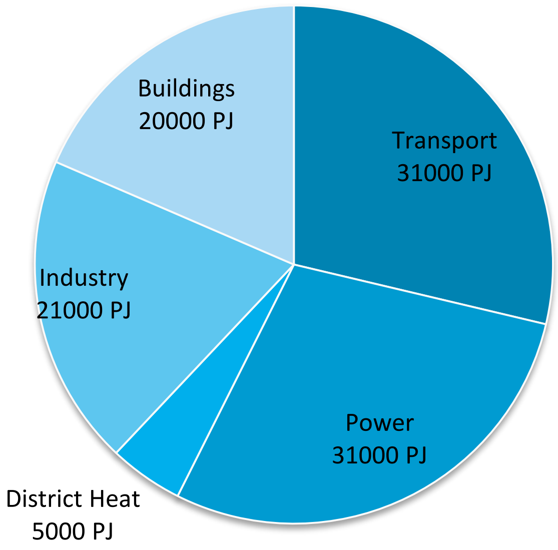

Figure 2: Breakdown of global biomass demand by sector based on REmap 2030

In order to evaluate the bioenergy potential from biomass, all three reports analyse the supply potential of different feedstocks. According to IRENA Remap (2014), agricultural residues are estimated to have a worldwide potential of 19000 – 48000 PJ/year. Energy crops' potential ranges between 33000 and 39000 PJ/year, forest products (including residues) account for 27000 – 43000 PJ/year, and waste potential holds a stable potential of 18000 PJ/year. Therefore,

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[14] As defined by IRENA (2019), the main difference between conventional and advanced biofuels is the sourcing of the feedstock. While conventional fuels may use feedstock that could typically be for food and animal feed, advanced biofuels are those that make use as feedstock of non-food and non-feed biomass, including waste materials (such as vegetable oils or animal fats) and energy-specific crops capable of being grown on less-productive and degraded land.

IRENA estimates that agricultural residues will make up for the majority of biomass supply in 2030. Forest residues will also be important for meeting bioenergy demand, though its potential is more difficult to estimate due to variation in sustainability criteria and environmental restrictions. The BioSustain project is in line with the IRENA Remap, as both conclude that the supply potential of 2030 will be well above today's levels and the EU-28 will meet future bioenergy demand easily, being able to provide between 10850 and 22700 PJ of bioenergy in 2030 (S2BIOM, 2014).

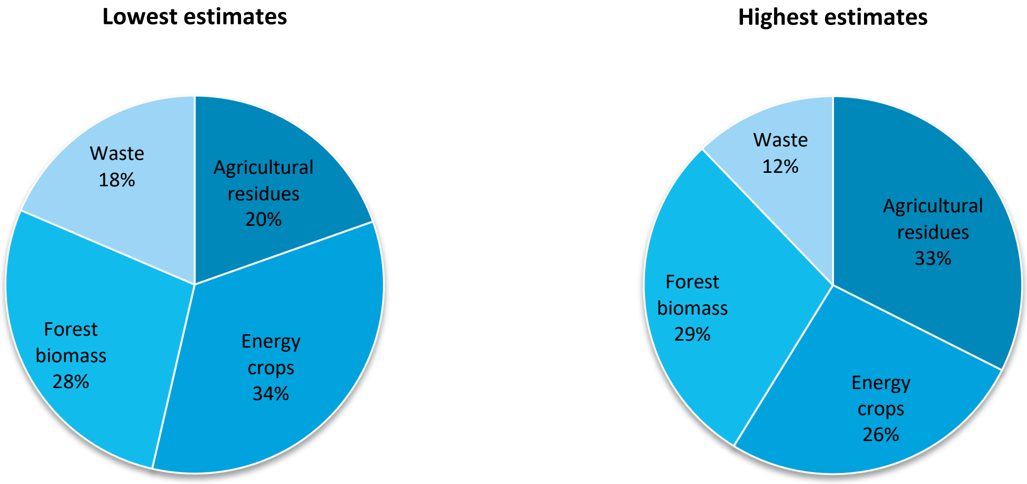

Figure 3: Global biomass potential by type of feedstock in 2030 based on REmap 2030

Forest biomass

Forest biomass is the most stable resource in terms of supply, as its potential increases only slightly from today's levels to those of 2030. In fact, according to S2BIOM, forest biomass is at the moment the most important source of renewable energy – making up around half of EU's total renewable energy consumption. The supply potential in 2030 is estimated to range between 79 to 146 Mtoe while demand is expected to be between 76 to 110 Mtoe. In 2030, the largest share of biomass supply will be from Germany (accounting for 15% of total European supply) and will be followed by France, Sweden, Finland and Portugal.

Energy crops

Regarding energy crops, BioSustain expects that the land available for its cultivation will grow from 4.5 Mha in 2012 to 24 Mha in 2030. Lignocellulosic crops have the highest potential in this category, and will increase from 11 Mtoe in 2012 to 113 Mtoe by 2030. According to S2BIOM, there will be plenty of land available where non-food lignocellulosic crops could be grown. The countries with largest supply potential of energy crops in Europe are Spain (18.4%), France (11.8%), Poland (11.7%), and Germany (9.5%), constituting more than 50% of European energy crop supply.

Agricultural residues and manure

Agricultural residues and manure will also be an important source for bioenergy supply in the future. Straw has the largest potential, though its low energy density could make it difficult to transport through long distances. Agricultural biogas is expected to account for the largest growth, increasing from 15 Mtoe in 2010 to 40 Mtoe in 2030. S2BIOM estimated that the total potential when accounting for primary agricultural residues (crops residues, pruning residues, livestock residues and others), and secondary agricultural residues (secondary crop and animal residues), would range between 3100 and 5200 PJ in 2030.

Waste

Bioenergy from waste may experience a large growth as well, going from around 11 Mtoe in 2012, up to 25-30Mtoe in 2030. Most waste biomass supply is expected to be consumed by bioenergy in 2030 (78%). Used animal fats and vegetable oils such as used cooking oil will constitute an important source for the supply of bioenergy and the production of advanced biofuel. In fact, used cooking oils are already traded between countries for this purpose. Further, four European countries will provide over 60% of biomass from waste sources by 2030 – UK (20.6%), France (15.1%). Germany (12.9%) and Spain (12.2%).

Overview

The table below presents a summary of the potential of different feedstock in Europe in 2030.

Table 10: Overview of feedstock potential in Europe

Feedstock	Energy Potential (2030) [PJ]	Main European Suppliers
Forest biomass	3307.5 – 6112.7	France, Sweden, Finland and Portugal
Energy crops	4731	Spain, France, Poland, and Germany
Agricultural residues	2450 – 2500	Mediterranean region, France, and Germany
Waste	1046.7 – 1256	UK, France, Germany, and Spain

3.3.2 Trade possibilities

Even though it is expected that Europe will be able to meet bioenergy demands without problem, some countries will have more potential to meet these targets than others. As explained in the previous section, the resource availability in The Netherlands is quite limited, meaning that the country will have to rely largely on imports in order to meet the bioenergy targets.

According to literature, Germany, France and Sweden will be key trading partners in Europe. Ukraine has also been appointed as a country with enough export potential by BioSustain, IRENA Remap, and S2BIOM. Due to their proximity to the Netherlands (and thus lower transportation costs), Germany and France yield the highest potential for export to The Netherlands. This report will therefore review the potential sources of bioenergy trade from these two countries. Given the large resource potential of Ukraine and Sweden, we will also analyse their export capacity for The Netherlands.

France

In the case of France, three papers have been reviewed to analyse the resource potential of the country and its trading capability. Simon, Tyner, & Jacquet (2009) performed an analysis of the biomass potential of agricultural residues and energy crops in France. Further, Forsell et al. (2013) studied the future use of biomass and biofuels in France and in Sweden. Finally, Searle & Malins (2015) analysed the amount of cellulosic wastes and residues that could be sustainably collected for use in cellulosic biofuel in the EU. Overall, these studies outline that the potential from France will come mainly from agricultural residues and, if energy demand increases, from energy crops as well. ICCT estimates that the availability of agricultural residues was approximately 50 million dry tonnes per year in 2015 for the production of biofuels (for all transport modes), equivalent to approximately 750 PJ per year (Searle & Malins, National case studies on potential waste and residue availability for cellulosic biofuel production in the EU, 2015). The paper estimates that the potential will grow to 60 million dry tonnes per year in 2030. In a recent study specifically for The Netherlands, ICCT estimates that 285000 dry tonnes per year could be imported from France for the production of biofuels for transport (Pavlenko & Searle, 2020). According to this study, France would not be able to scale-up the biofuel industry in time to process the entire availability of national agricultural residues. Straw and stalks are the main source of agricultural residues in France, whereas miscanthus and short rotation coppices constitute the energy crops with highest potential.

The potential of agricultural residues will depend highly in the removal rate[15], which in France is estimated to be between 38.5% and 53%, and under certain conditions up to 60%. The results of the analysis by Simon et al. (2009) showed that agricultural residues alone were capable of providing 67% of the biodiesel production target for 2015 (2.8 billion litres). Moreover, agricultural residues provide a financially better alternative to energy crops, as their production cost per litre was estimated to be €0.35/litre compared to €0.61/litre from miscanthus. However, this is only true for the short term. The high biomass yield from miscanthus together with its more uniform characteristics can lead to this crop becoming more attractive than agricultural residues in the future. An increase of bioenergy demand for instance could play a role in making energy crops more competitive - according to Forsell et al. (2013), the use of energy crops in France is expected to increase as demand for bioenergy goes up. Overall, both studies indicate that domestic biomass will entail a significant source for total energy supply in France in the future, specifically up to 1470 PJ in 2050.

Regarding trading capabilities, the regions of Nord Pas de Calais, Picardie, and Champagne-Ardenne, could be potential exporters to The Netherlands due to their location and notable biomass capacity (Simon et al., 2009). More research is needed to determine the actual technical and economic potential of exporting feedstock sources from these regions to The Netherlands.

Germany

In order to analyse the feedstock potential from Germany, three papers have been reviewed: Poeschl, Ward, & Owende, *Prospects for expanded utilization of biogas in Germany* (2010), Thornley, Chong, & Bridgwater, *European biorefineries: Implications for land, trade and employment* (2014), and Aust et al., *Land availability and potential biomass production with poplar and willow short rotation coppices in Germany* (2013). Though the scope varies slightly through these papers, the core of the papers remains the same – assess the biomass potential of Germany.

In 2010, the estimated area dedicated to grow energy crops for biogas plants in Germany was 400000 ha (Poeschl, Ward, & Owende, 2010), which can be translated into an energy potential of 236 PJ annually. On the other hand, crop residues accounted for 13.7 PJ per annum, and feedstock from industrial sector and municipal solid waste for 9.3 PJ and 12.5 PJ per annum, respectively. Currently, production of bioenergy from animal waste and agricultural residues is popular in Germany. Moreover, about 2 million ha of land are used to grow energy crops – usually miscanthus, ryegrass and clover, tough other studies point out Silphie and Sudan Grass as promising feedstock for bioenergy production as well. Aust et al. (2013) also identified short rotation coppices (SRC) as an energy crop with great potential in Germany, especially in the north and east regions of the country. However, after taking into account several restrictions and future climate predictions, the paper concluded that the potential for growing SRC could switch to the south of Germany, to the Bavarian region. Nevertheless, some locations in north-western Germany still hold good potential. Thornley et al. (2014) estimate that Germany could have the capability to support 6 biorefinery facilities (3000 ktpa), being energy crops (e.g. miscanthus, SRC) the most promising feedstock. According to ICCT, in 2015 Germany had approximately 40 million dry tones of agricultural residues available for the production of biofuels (for all transport modes), equivalent to approximately 600 PJ per year (Searle & Malins, 2015).

Literature estimations on Germany's supply potential vary notably – from 250 PJ to 1760 PJ in 2050 (Szarkaa, Eichhornb, Kittlera, Bezamab, & Daniela Thränab , 2017). However, there is consensus in that woody biomass and energy crops hold a great potential for bioenergy in Germany. It would therefore be interesting for The Netherland to

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[15] The removal rate refers to the percentage of available residues that can be collected without increasing soil erosion or diminishing soil fertility

study the export potential from the North West regions of the country, taking into account transport costs and overall technical, sustainable and economic viability of the export.

Sweden

According to Mustapha, Trømborg & Bolkesjø (2017) the Nordic European countries are believed to be leaders of the global forest industry, and they are likely to be the countries that will most easily fulfil the bioenergy targets set by the European Union in the Renewable Energy Directive. Sweden specifically has been pointed out as the Nordic country with the largest potential of feedstock allocation for the production of biofuel. Forsell et al. (2013) found that the use of woody biomass for bioenergy generation will be stable over time, though SRC use is expected to decrease as bioenergy demand increases. This is a consequence of other energy crops such as starch and oil crops being more cost-effective to produce than SRC. Forest residues are also expected to play a key role in meeting bioenergy demand in the future. However, it should be noted that the transport of forest residues is expensive, increase its price and therefore making it less competitive for trading.

Ukraine

Ukraine on the other hand has frequently been mentioned as an important source for biomass trade. Schaffartzik, Plank & Brad (2014) indicate that approximately half of the land available for biofuel feedstock production in Europe in 2030 will be allocated in Ukraine (between 21.8 and 22.6 Mha). This area constitutes half of Ukraine's agricultural area and 2/3rd of its arable land. Consequently, according to the authors the use of this land will imply notable trade-offs with other types of land use. Therefore, even though Ukraine has the potential to trade important feedstocks for biofuel such as rapeseed, wheat, maize, sugar beets or sunflower seeds, it would imply large economical, sustainable, and social trade-offs. However, a more recent study conducted by Pietkun-Greber & Ratuszny (2017) concludes that Ukraine does have enough energy to meet the domestic and international demand. According to the latter authors, the use of marginal lands to grow energy crops (especially miscanthus) and raw materials for biofuels will optimise the potential of the country. Overall, the total supply potential of Ukraine in 2050 is estimated to be 1758 PJ (Diachuk, 2018).

Overview of trade potential and factors

A summary of the 2050 supply potential per analysed country can be seen in Table 9 below. Overall, France and Germany were found to be the countries with the highest supply potential out of the four countries analysed. However, this should be seen as a theoretical potential, as there are many factors that can influence the true trading potential between countries. When assessing the trading potential of biomass for bioenergy, literature looks into the technical and the sustainable or realisable potential of the biomass. The technical trade potential is the potential that could be achieved with the current available technologies, infrastructure and techniques for harvesting and processing the feedstock, whereas the sustainable potential takes into account economic, environmental and societal aspects such as finance needs for energy deployment or energy security, direct and indirect land use change, life cycle greenhouse gas emissions, water use, biodiversity, soil quality issues, food security and employment (2014). Moreover, the transportation and bioenergy logistics costs also play a role in determining the economic viability of the trade (BioSustain, 2017).

Assessing the technical, sustainable and economic potential for biomass trade is of great importance as it provides information on the viability and the overall sustainability of the trading, which can turn out to be not beneficial for the environment or society due to the many factors described above.

Consequently, after determining that the higher theoretical potential for The Netherlands lies on France and Germany, follow-up research should look into the technical, economical and sustainable potential for the most promising feedstock in these two countries – energy crops and agricultural residues.

Table 11: Overview of supply potential from Germany, France, Sweden and Ukraine

Country	Total Supply Potential in 2050 [PJ]	Main feedstock
Germany	250 – 1760	Energy crops (miscanthus, SRC) and agricultural residues
France	1470	Energy crops (miscanthus) and agricultural residues
Sweden	250	Woody biomass
Ukraine	1758	Energy crops
Total	**5488**	
Maximum realistic amount for trade with NL	604	11% of total, based on share of NL international aviation energy balance w.r.t. EU27 (eurostat, 2020)

3.3.3 Overview

In summary, literature shows that non-food lignocellulosic energy crops and agricultural residues are the feedstocks with highest potential in Europe. Woody biomass and waste will be important feedstocks as well, though their supply potential will stay relatively stable overtime. Overall, European biomass potential will vary between 10850 and 22700 PJ in 2030. In terms of trade, it is clear that there is capacity in Europe to allow the Netherlands to import feedstock from neighbour countries. Germany and France seem to be the countries with the higher theoretical potential for export to The Netherlands. Ukraine is predicted to have large availability for export too. However, research needs to be conducted to assess the viability of trade between Ukraine and The Netherlands in terms of technical and sustainable feasibility. Overall, more research is needed to assess the economic, sustainable and technical aspects linked to this trade and determine which feedstock and country would better fit the bioenergy needs from the Netherlands.

3.4 Conversion of feedstocks to jet fuel

In Sections 3.2 and 3.3, estimations of the availability of organic feedstocks in the Netherlands and the EU in 2050 were given in petajoules. This cannot be directly assumed to be the energetic value of the fuel which can be produced from these feedstocks, as the energy input needed for production (and, to lesser extent, storage and transportation) of fuel causes energy losses from feedstock to fuel. For biofuels, these energy losses are estimated by the ICCT to be around 55%, the so called well to tank efficiency. Using this ballpark figure, Table 12 gives the estimated available amount of jet fuel which can be produced in the Netherlands and Europe from organic feedstocks in 2050. (Searle, 2018) The amount of feedstocks available in 2050 from Table 9 and Table 11 was used.

Table 12: Estimated amount of SAF which can be produced from available biomass in NL and EU

Resources	Estimated amount of SAF to be produced [PJ]
NL “freely available and additional” biomass 2050	35
EU (DE, FR, SE and UA) Maximum realistic amount of biomass for trade with NL	332

4 Feedstocks and resources for e-fuels

E-fuels are synthetic fuels, created from inorganic substances through chemical reactions using (preferably renewable) electricity. For aviation, hydrogen and synthetic kerosene-like compounds (synthetic jet fuel) are currently being examined as low-carbon options to replace fossil kerosene. In this chapter, only e-fuels produced from renewable energy sources as specified in the RED II requirements are considered.

A schematic overview of synthetic fuel or power to liquid (PtL) production is given in Figure 4. The required compounds for synthesis are hydrogen (H_2) and carbon dioxide (CO_2). Energy input in the form of electricity is required to produce these from primary resources, which are water and a concentrated or diluted air stream respectively. The processes to obtain hydrogen and carbon dioxide are explained in detail in Section 4.1. Once obtained, hydrogen and carbon dioxide are chemically combined to form hydrocarbons, which are molecules with a carbon backbone and predominantly hydrogen attached. The molecules in the kerosene fraction on average contain 9 to 13 carbon molecules. For this reason, more energy is needed for production of jet fuel than for example synthetic gasoline, which has five to six carbon molecules. The certified pathways towards and the required chemical properties of synthetic jet fuel are described by ASTM D7566. In this chapter, production of synthetic jet fuel via the FT pathway is considered.

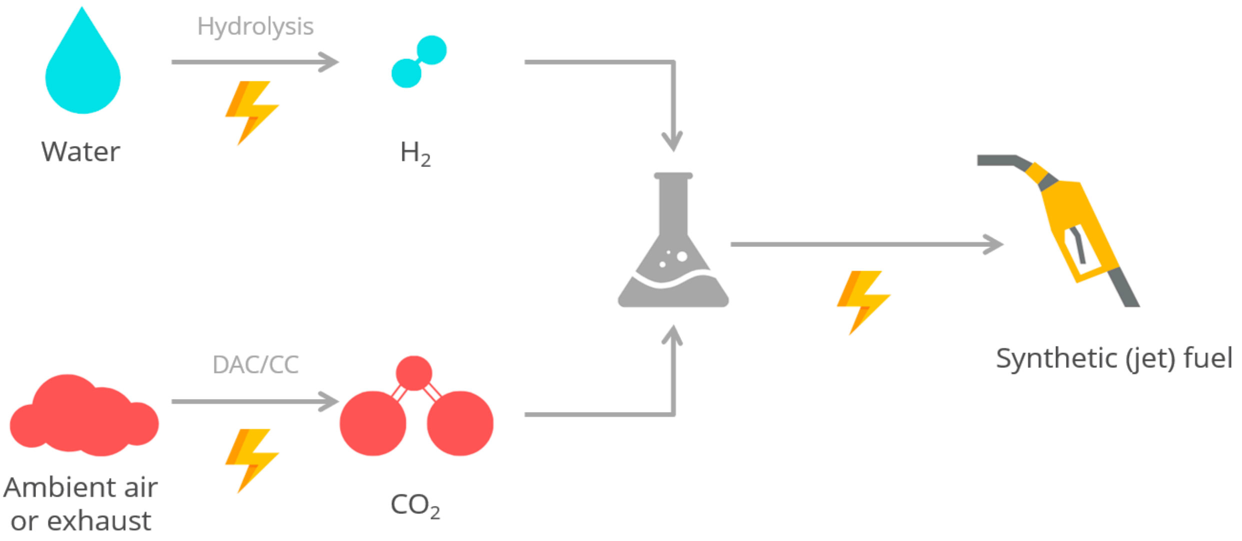

Figure 4: Process overview of producing synthetic (jet) fuel from primary resource. Lightning bolts indicate that energy input is required for a step

This chapter will examine the three main resources needed to produce synthetic kerosene: renewable electricity, hydrogen and an inorganic carbon source. Synthetic kerosene has abundant physical feedstocks, due to the theoretically large availability of hydrogen and carbon dioxide molecules on earth. Therefore, renewable electricity will be the limiting factor in the amount of jet fuel which will be produced in the future; as all steps in the process of producing synthetic jet fuel need energy input and therefore cause efficiency losses (Shell, 2018; Yugo & Soler, 2019).

4.1 Description of resources

This chapter describes the resources required for producing synthetic (jet) fuel, starting with renewable electricity in Section 4.1.1, followed by hydrogen in Section 4.1.2 and inorganic carbon in Section 4.1.3.

4.1.1 Renewable energy

Following the RED II, renewable energy (or 'energy from renewable sources') is defined as energy "from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas" (EP, 2018, art. 2). It is emphasised that nuclear energy is considered as a non-renewable energy source in this report, even though it is a form of non-carbon energy.

In the Netherlands, wind and solar energy are the best known and most widely available sources of renewable energy.

4.1.2 Hydrogen

This section describes the use of hydrogen as both a fuel and a feedstock to make aviation more sustainable. The role of hydrogen to decarbonize aviation has recently gained much interest as multiple publications highlight its importance to reach climate commitments. Hydrogen can be used as a feedstock for the production of power to liquid fuels, or as a fuel to power the aircraft by using fuel cells or by direct combustion in the engine. H_2 does not contain carbon molecules and therefore it does not cause CO_2 emissions during its use. When used as a fuel, it offers the opportunity to fully decarbonize aviation. When used as feedstock, H_2 is combined with CO_2 to produce synthetic fuels which have similar physical properties to fossil kerosene. In order for these synthetic fuels to reach net-zero emissions, the CO_2 needs to be captured from the air by using renewable electricity.

Hydrogen can be used **as fuel** to power the aircraft:
- In combination with fuel cells
- In combination with combustion engines

Or **as feedstock**:
- For the production of power to liquid fuels
- For the production of biofuels and other production routes

This section describes the production of hydrogen, the associated costs and the potential availability of hydrogen in the Netherlands and in the EU.

4.1.2.1 Production processes

In nature, hydrogen exists bound to other molecules. For energy use however, hydrogen is used in the form H_2 which can be produced by using a variety of production processes. These processes differ based on the type of technology and the type of the primary energy carrier.

As shown in Figure 5, hydrogen is nowadays mainly produced by using fossil sources. Even the small amount (5%) produced by using electricity only partially stems from renewable sources such as solar and wind. In the future, the mix of feedstocks is expected to change towards much larger portions of renewable electricity.

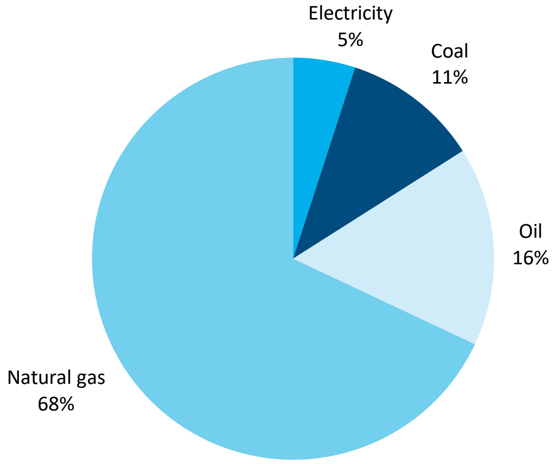

Figure 5: Primary energy carriers for the production of hydrogen globally (Shell & Wuppertal Institut, 2017)

The production processes used today can be grouped in three categories: electrolysis, thermochemical conversion and biochemical conversion. These processes can be further split according to the technology used. An overview of the production processes with the associated feedstock and maturity level is given in Table 13.

Globally the most common production process is steam reforming of natural gas. In the EU the production of hydrogen from fossil sources currently causes the release of 70 to 100 million tonnes of CO_2 annually (EC, 2020). In July 2020, the European Commission published “A hydrogen strategy for a climate-neutral Europe” where it outlines the expected role of hydrogen in decarbonizing the EU economy and reaching the climate neutral target in 2050 as stated in the European Green Deal (EC, 2020). The roadmap foresees a drastic increase in the production of hydrogen by using electrolysis of renewable electricity to lower CO_2 emissions. This shift is reflected in global investments in electrolysers which between November 2019 and March 2020 have increased from 3.2 GW to 8.2 GW by 2030, of which 57% in Europe.

Table 13: Overview of hydrogen production processes including the associated feedstocks and maturity level (Holladay, Hu, King, & Wang, 2009)

Technology	Feedstocks	Maturity level
Steam reforming	Hydrocarbons	Commercial
Partial oxidation	Hydrocarbons	Commercial
Biomass gasification	Biomass	Commercial
Alkaline electrolyser	Water + electricity	Commercial
Autothermal reforming	Hydrocarbons	Near term
Ammonia reforming	Ammonia	Near term
PEM electrolyser	Water + electricity	Near term
Aqueous phase reforming	Carbohydrates	Medium term
Solid Oxide electrolysis cells	Water + electricity + heat	Medium term
Plasma reforming	Hydrocarbons	Long term
Photolysis	Sunlight + water	Long term
Dark fermentation	Biomass	Long term

Technology	Feedstocks	Maturity level
Photo fermentation	Biomass + sunlight	Long term
Microbial electrolysis cells	Biomass + electricity	Long term
Thermochemical water splitting	Water + heat	Long term
Photoeletrochemical water splitting	Water + sunlight	Long term

Depending on the amount of carbon emissions hydrogen can be categorized in:
- green hydrogen;
- blue hydrogen;
- grey hydrogen.

Grey hydrogen is produced with fossil sources. Blue hydrogen is also produced with fossil sources, but the CO_2 is partially captured and stored underground thereby lowering the overall emissions. Green hydrogen is produced with renewable energy sources such as renewable electricity and biomass.

Blue hydrogen is mainly seen as an intermediate option while the production of green hydrogen scales up and the costs of green hydrogen decrease. Also for the Netherlands this option may in the near future be considered to lower emissions. The following aspects should however be taken into account according to IRENA when considering the deployment of blue hydrogen (IRENA, 2019):
- CCS should be included from the start;
- a part of the CO_2 is usually leaked (around 5-15%);
- monitoring, reporting and verification are necessary to maximise storage rate;
- remaining emissions should be correctly accounted for;
- using the CO_2 for the production of power to liquid fuels only achieves halving of emissions;
- investments may be diverted from renewable energy projects.

This report focuses on feedstocks for the production of sustainable aviation fuels which meet the RED II sustainability criteria. Therefore the production of green hydrogen is further elaborated. The limited availability of biomass, as shown in Chapter 2, makes the use of electrolysis of renewable electricity the most promising option for large scale production. The production of hydrogen by using biomass feedstocks could in some circumstances also be applied, but will remain limited in overall availability.

Thermochemical and biochemical conversion of biomass

Gasification of biomass into synthesis gas can be applied followed by further treatment to produce H_2. Mostly solid biomass feedstocks can be used for this process. Another route is the fermentation of moist biomass for production of biogas. Biogas can then be converted to hydrogen by following the same process as natural gas.

Electrolysis of renewable electricity

The electrolysis breaks down water into hydrogen and oxygen by electricity. Electrolysers consist of an anode and a cathode separated by an electrolyte. Four main types of electrolysers are further described in this section: Alkaline Electrolysis (AE), Proton Exchange Membrane Electrolysis (PEM), Anion Exchange Membrane Electrolysis (AEM) and Solid Oxide Electrolysis (SOE).

An overview of the characteristics of electrolysers is given in Table 14 based on a Shell hydrogen study (Shell & Wuppertal Institut, 2017). The efficiencies are similar to other sources which identify an efficiency range of 54 – 85% for alkaline electrolysers and 52 – 79% for PEM electrolysers (Kaveh Rajab Khalilpo, 2019).

Table 14: Overview of electrolyser types and properties (Shell & Wuppertal Institut, 2017)

Type	Temperature range	Efficiency	Lifespan	TRL
Alkaline Electrolysis (AE)	60 – 80	65 – 82 %	60000 – 90000 h	Commercially used in industry for the last 100 years
Proton Exchange Membrane Electrolysis (PEM)	60 – 80	65 – 78 %	20000 – 60000 h	Commercially used for medium and small applications
Anion Exchange Membrane Electrolysis (AEM)	60 – 80	N/A	N/A	Commercially available for limited applications
Solid Oxide Electrolysis (SOE)	700 – 900	85 % (lab)	approx 1000 h	Experimental stage

The main advantages and disadvantages of the types of electrolysers are given in Table 15.

Table 15: Drivers and barriers of electrolyser technologies (Kaveh Rajab Khalilpo, 2019)

Type	Drivers	Barriers
Alkaline	Low installation costs, commercially available, long life span	Not flexible with variable input power, high maintenance
PEM	Flexible with variable input power, first commercial applications	Short life span
SOE	Superior efficiency	Early stage of development, challenges with heat integration

HYDROGEN PRODUCTION IN THE EUROPEAN UNION

The recent hydrogen strategy published by the EC shows two timeframes for the production of hydrogen (EC, 2020). Up to 2030 hydrogen is produced as a mix of green and blue hydrogen, thereby also using fossil sources in combination with CCS to limit emissions. The objective includes the installation of 40 GW of renewable hydrogen electrolysers and the production of up to 10 Mt of renewable hydrogen. After 2030 only the production of green hydrogen is deemed suitable to meet the goals of a climate neutral continent. Towards 2050 this requires a massive increase in renewable electricity production as about a quarter is expected to be used for hydrogen production.

Hydrogen Europe has recently published a report which shows the European demand in 2030 combined with an analysis of the amount of green and blue hydrogen that can be produced in the EU and imported from outside the EU. To meet demand, 3 Mt of green hydrogen (18% of total) is expected to be imported from Ukraine and North Africa and 4,4 Mt of green hydrogen (26% of total) is expected to be produced in the EU. The production of 4,4 Mt would require the realization of 40 GW electrolyser capacity, which requires 80 GW of additional renewable electricity installations. The remaining hydrogen (around 10 Mt) is produced from natural gas and coal by using carbon capture and storage thereby reducing emissions up to 90-100%.

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Table 16: European demand in 2030 and expected production in 2030 (Hydrogen Europe, 2020)

Demand		**Production**	
FCH JU Hydrogen Roadmap Europe	Mt H_2	Hydrogen Europe 2 × 40W GW Green Hydrogen Initiative	Mt H_2
Existing feedstock	9,1	Eu production green H_2	4,4
New feedstock (steel, kerosene)	2,5	Import green H_2	3,0
Transport	1,8	Grey to low carbon H_2 gas SMR with CCS/CCU, 90% CO_2 emission reduction and low-carbon electrolysis	8,2
Power balancing	1,5	New low carbon H_2 coal gasification with CCS/CCU nearly 100% CO_2 emission reduction	1,3
Total	**16,9**	**Total**	**16,9**

4.1.3 Inorganic carbon

As mentioned in the introduction of Chapter 4, inorganic carbon is an essential resource for the production of synthetic fuels. There are two primary routes to obtain inorganic carbon in CO_2 or CO form: direct air capture and recycled carbon. This paragraph will explain the concept and state of the art of both methods.

4.1.3.1 Direct Air Capture

Direct air capture (DAC) entails the separation and subsequent removal of CO_2 from ambient air (or diluted gases). DAC tends to generate quite some buzz, because removing carbon from the atmosphere (in large quantities) may have the potential to reduce anthropogenic climate change. On average, ambient air consists of carbon dioxide for 0,033% volume or 400 ppm. This is the maximum which can be captured by DAC. Most DAC systems rely on adsorption, which entails the binding of CO_2 molecules to another molecule. A schematic overview of the working of such DAC systems, is given in Figure 6. In the installation, fans blow air through contactors, leading to CO_2 being bound to a sorbent. Chemically, this process needs no external energy input. However, due to the low concentration of CO2 in ambient air, the fans are needed to constantly provide new molecules to the contactor area. When the contactor is close to saturation, heat is used to release the carbon dioxide molecules in a concentrated stream and the gas is compressed to desired pressure. The sorbent has been regenerated. Most commercial DAC pilots (Climeworks, Skytree, Global Thermostat, Anthecy, Carbon Engineering) use this method, although some rely on a solid sorbent and others on liquid (Terwel & Kerkhoven, 2018). The demand for Direct Air Capture up to 2050 according to Fasihi, Efimova, & Breyer (2019) is presented in Appendix C.

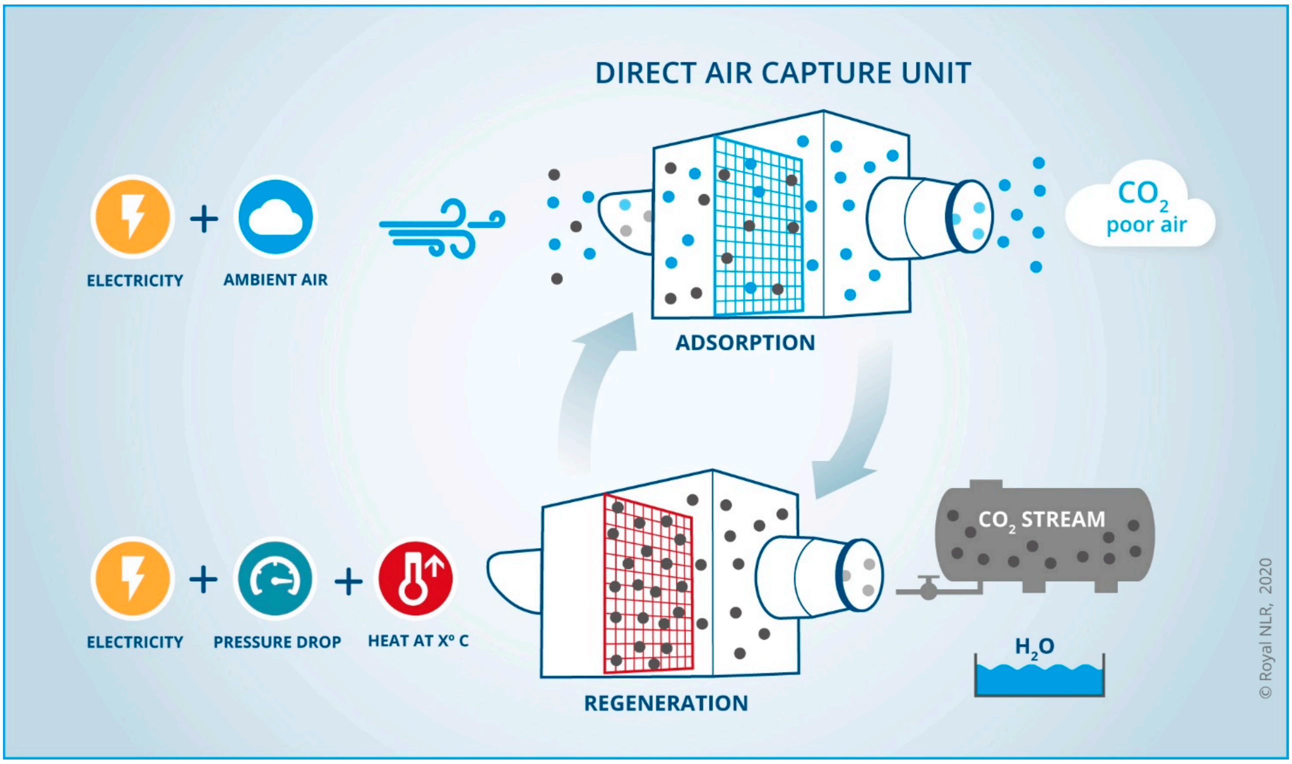

Figure 6: Schematic overview of a general DAC system (based on the work of Fasihi, Efimova, & Breyer, 2019)

State of the art

Research into DAC is nothing new; it has been under development since the 1930s and the first operational systems were finished in the 1950s, primarily focused on maintaining a habitable environment for spaceflight (Fasihi, Efimova, & Breyer, 2019).

At present, the efficiency of several liquid and solid sorbents has been characterised theoretically and practically, and several innovative suggestions have been made to lower the energy requirement of the DAC process, for example by using heat from exothermal synthetic fuel production processes to release CO_2 from the sorbent (Choi, 2011).

Several companies are commercially developing DAC:

- Climeworks has three operational low temperature solid sorbent pilot plants in Dresden, Switzerland and Iceland. They are targeting a 75€/tCO_2 DAC cost (Climeworks, 2018). Climeworks merged with Dutch DAC start-up Antecy in 2019.
- Global Thermsostat, another company relying on low temperature DAC, has been operating pilot plants in California since 2010. They utilize waste heat from industrial processes to decrease energy demand. They have stated that a 11-24€/ton CO_2 price is their target (Kintisch, 2014).
- Carbon Engineering, a company co-founded by Bill Gates, opened their 1T CO_2/day liquid DAC pilot plant in 2015.
- A Dutch start-up active in this field is Skytree, which was founded in 2008 and uses electrostatic adsorption and moisture desorption (Fasihi, Efimova, & Breyer, 2019).

Rotterdam The Hague Airport will be piloting a DAC and fuel synthesis plant in which the DAC technology is provided by Climeworks and Urban Crossovers.

4.1.3.2 Recycled carbon

In the case of recycled carbon, carbon dioxide which is emitted by a point source, for example an industrial process, is captured (usually via Carbon Capture and Storage (CCS) or Carbon Capture and Use (CCU) schemes) and repurposed. Using this concentrated carbon dioxide for the production of synthetic fuels is more energy efficient than employing direct air capture, as less energy is expended to purify carbon dioxide from other gases. Furthermore, storage of large amounts of carbon is inconvenient and poses environmental risks (Lam, 2012), so proponents of using recycled carbon for synthetic fuels argue that since we have these streams of carbon, we should repurpose them as usefully as possible. Opponents see the use of recycled carbon as prolonged dependence on fossil fuels, and they fear that demand for recycled carbon will weaken the incentive for industrial parties to reduce emissions.

The RED II defines recycled carbon fuels as liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process of industrial installations (European Commission, 2019).

Aside from possible uses of recycled carbon, the capturing and storage of carbon dioxide to prevent release into the atmosphere is seen as an important short term solution to achieve climate targets. In the coalition agreement of the Rutte III-cabinet in the Netherlands, CCS is explicitly mentioned as an essential technology to reduce carbon emissions in the Netherlands (VVD, CDA, D66 & Christenunie, 2017). Therefore it is expected that more carbon will be captured and stored in the future.

State of the art

There are generally three steps to be taken in carbon capture from point sources: CO_2 capture, CO_2 transportation and, if required, CO_2 storage. The separation and capture of CO_2 from other exhaust substances is generally done via one of the following methods (Figueroa, 2008; Singh & Dhar, 2019):

- **Chemical absorption**
  In this case, CO_2 is dissolved in a liquid and absorbed by other compounds, and subsequently desorbed and released back to gaseous form. Monoethanolamine, potassium hydroxide and ionic liquids can be used for this. An advantage of this technique is thermal stability. Ionic liquids are also environmentally safe. However, disadvantages of this technique include solvent loss due to evaporation, solvent degeneration upon contact with other compounds such as SO_2, high energy consumption for solvent regeneration and equipment corrosion.
- **Physical adsorption**
  Carbon dioxide is adsorbed to a solid such as carbon dioxide, sodium carbonate, calcium oxide or zeolite, or a Metal Organic Framework (MOF). An advantage of this carbon capture technology is the low amount of waste which is generated, but a disadvantage is the energy inefficiency and the contamination with other compounds, requiring a flue gas treatment.
- **Membrane separation**
  In this technique, CO2 is physically separated from other components by use of a selectively permeable membrane; this means that the membrane only allows CO_2 to travel across it. Polymeric membranes are most used for this purpose. The main advantages are high separation efficiency and small installation requirements. However, due to cooling requirements this technology is energy intensive and the large surface area of membrane needed leads to high costs.
- **Cryogenic distillation**
  Firstly, the exhaust stream is refrigerated. Subsequently, the gas mixture is condensed at different temperatures to separate CO_2 from the other compounds. An important advantage of this method is the high capture efficiency; up to 99,9%. However, refrigeration requires a large energy input, flue gas removal is necessary in between phases and solidified CO_2 continuously needs to be removed from heat exchange surfaces

After separation from other exhaust compounds, the concentrated stream of CO_2 is transported, generally via pipeline or ship, to the location where it will be reused or stored.

In some cases, CO_2 does not have to be separated, as a (almost) pure stream of CO_2 is generated by an industrial process. This is the case for the CO_2 generated at Shell Pernis, as the Shell Gasification Hydrogen Plant produces hydrogen from methane, which leaves CO_2 as a rest stream. The CO_2 is directed from Pernis to agricultural companies in the Westland region of the Netherlands via pipelines (Shell, 2019). In such cases where (almost) pure CO_2 is readily available, carbon recycling is more economical and energy efficient than in the case that it needs to be separated.

4.2 Availability of renewable electricity in NL

As noted in the introduction of this chapter, the production of e-fuels requires substantial amounts of energy. This section presents the results of an investigation into the amount of available renewable electricity produced in the Netherlands in 2050. To the extent consistent information is available, both power (GW) and energy content (PJ/TWh) are addressed. Grid capacity has not been taken into account. Following Section 4.1.1, nuclear energy has not been taken into account.

It is important to stress that, as this research does not concern itself with the question of how such electricity should or could be divided, ‘available’ renewable electricity should be interpreted as ‘available’ for all uses. This also means that, at least in theory, the entire energy content of available electricity is required or allocated to other functions than the production of e-fuels for air transport. This is heavily dependent on possible reductions in energy demand across the entire economy.

4.2.1 Methodology

The Dutch Climate Law (Rijksoverheid, 2019), which was sets a framework for the development of policy to reduce Dutch greenhouse gas emissions and thereby limit climate change, the Dutch energy system must have 95% lower emissions in 2050 compared to 1990[16]. Various publications have investigated the electricity supply and demand in the Dutch energy system in 2050. Specifically, the following three reports have been considered[17]:

- A consortium of organisations has in January 2018 published the *Ruimtelijke verkenning energie en klimaat*, which presents the potential for renewable electricity generation in The Netherlands, from numerous sources (Kuijers, et al., 2018);
- Berenschot has in May 2018 delivered a quick scan commissioned by the Ministry of Economic Affairs and Climate Policies in which various roadmaps and future scenarios for 2030 and 2050 are analysed and compared (den Ouden, Lintmeijer, Bianchi, & Warnaars, 2018);
- Berenschot and Kalavasta have in March 2020 delivered a report supporting the *Integrale infrastructuurverkenning (II3050)* and subsequently the Dutch National Climate Agreement presenting four climate-neutral energy scenarios for 2050 (den Ouden, et al., 2020).

It is important to discern between two study approaches, both represented in the literature considered. Studies that take an approach here referred to as ‘top-down’ first investigate the energy demand (including the effect of possible efficiency improvements) and subsequently analyse how this demand can be met. Given the fact that most reports that are specific to the energy production potential in the Netherlands are produced in connection to or in the context of the Dutch National Climate Agreement or Dutch Climate Law, they focus on the use of energy covered by the Nationally Determined Contributions (NDCs) of the Paris Agreement. International aviation and shipping (IAS) are explicitly not part of these. As such, such top-down studies might be pessimistic in the total anticipated electricity supply, as they never considered IAS energy demand to begin with, and as such have not looked for electricity generation capacity to meet that.

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[16] Given the European Green Deal and Climate Law, the authors deem it likely for this target to be increased to a 100% reduction compared to 1990 or – equivalently – reaching net zero CO_2 emissions by 2050.

[17] In addition to these three publications, TNO has in May 2020 delivered a report commissioned by the Ministry of Economic Affairs and Climate Policy outlining two scenarios towards a sustainable energy system for the Netherlands in 2050 (Scheepers, et al., 2020). Due to a seemingly different calculation method, the results by Scheepers et al. have not been integrated into this review. Where relevant, the information is used for (qualitative) validation purposes.

On the other hand, there are ‘bottom-up’ reports which determine the total potential for electricity generation, to a large extent regardless of their use. The analysis presented in this report aims to combine these two, thereby – at least to some extent – addressing the topic of electricity availability for international aviation. Bottom-up approaches are used to find total potential and top-down studies yield the anticipated demand for NDC-energy: the different is (theoretically) available to IAS.

4.2.2 Potential for renewable electricity generation

This section presents the potential for renewable electricity generation in The Netherlands from a host of energy sourced, based on Kuijers et al. (2018, Section 2.3). Table 17 summarises their results. Potentials between parentheses are estimated by the current author.

Table 17: Potential for renewable electricity generation in The Netherlands in 2050, estimated by Kuijers et al. (2018)

Source	Specification	Potential [PJ / GW]	
		Theoretical	Realistic
Wind at sea	10-14MW turbines, 18.000km^2, 4-6 MW/km^2 (th.) to 2-3MW/km^2 (real.)[18, 19]	1000-1500 / 72-108	500-750 / 36-54[20]
Wind on land	On land, 3MW turbines (current size)	475 / 50	
	Internal waters	100 / (10.5)	
	Natuur Netwerk Nederland	225 / 25	
	Repowering current installations (> 3MW)	50 / 5	
	New wind energy landscapes	35 / 4.2	15-35 / 1.9-4.2
	Local installations (2.4kW at farmsteads, 2.3MW as ‘town turbine’)	51 / 5.7	
	Total wind on land	**936 / 100**	**916 / 98-100**
Solar	On roofs, theoretical 30% panel efficiency at 100% of suitable roof area (325 km^2), realistic 26% efficiency at 75% roof area	200 / 65	90-150 / 30-50
	On 10% of agricultural lands	450-750 / 150-250	
	On 15% of 22 km^2 land fill areas	2 / (0.5)	
	On 10% of agricultural lands with soil salinisation	50-85 / 16-30	
	Surrounding infrastructure (e.g. noise barriers)	25-45 / 9-15	
	On 15% of wasteland (400 km^2)	15 / (5)	
	On 10% of internal waters	70 / 22	
	Total solar	**812-1167 / 268-388**	**702-1117 / 233-373**
Water	Water (current, tides, waves, osmosis)	31 /	
Geothermal	For electricity generation, depth of 4-7 km	35 / 1.35	
Total		**2814-3669 / 441-597**	**2184-2869 / (368-528)**

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[18] The 18.000 km^2 does take into account protected areas and interests such as maritime routes, but does not discount for fishing.

[19] If electricity production from wind at sea rises to 11 GW by 2030 (see footnote 20), 2.8% of the Dutch part of the North Sea will be used for wind power generation (Rijksoverheid, n.d., c). PBL has investigated post-2030 spatial coverages. For offshore wind power capacities of 32 and 60GW, comparable to the ‘realistic’ values presented here, spatial coverage will be 9 to 14% and 17% to 26% of the Dutch continental shelf (Matthijsen, Dammers, & Elzenga, 2018), measuring 57.800 km^2 (Rijksoverheid, n.d., c). The PBL-analyses uses power densities of 4 MW/km^2 (lower theoretical value by Kuijers et al.) to 9 MW/km^2; Rijksoverheid (n.d., c) foresees 10 MW/km^2. Using these power densities, the 18.000 km^2 noted by Kuijers et al. (2018) yields a potential of 72 to 162 GW or even 180 GW.

[20] By 2030, electricity production from wind at sea will be approximately 11 GW (Rijksoverheid, n.d., a), delivering some 175 to 180 PJ of electricity per year (Rijksoverheid, n.d., b). For the period 2030 to 2040, additional capacity of 20 to 40 GW is foreseen (OFL, 2020); the Dutch Climate Agreement notes “growth possibilities to a maximum of 60 GW” for 2050 (translated from Voortgangsoverleg Klimaatakkoord, 2019, p. 159). As such, values identified by Kuijers et al. (2018) are indeed deemed realistic.

The total realistic potential from wind, solar, water and geothermal energy is estimated to be between 2184 and 2869 PJ (upwards of 368 to 528 GW). Assuming theoretical potentials wherever known, these estimates rise to 2814 and 3669 PJ (upwards of 441 to 597 GW). Combining these, a range of 2184 to 3669 PJ (upwards of 368 to 597 GW) is found.

Scheepers et al. (2020) estimates that more than 99% of the electricity supply will stem from solar and wind power, regardless of the scenario chosen. This is largely consistent with the results presented in Table 17.

4.2.3 Anticipated electricity demand

This section presents the anticipated electricity – or sometimes more general: energy – demand in The Netherlands, based on a number of sources.

Nationaal Perspectief Energie en Ruimte, in Kuijers et al. (2018)
Kuijers et al. (2018, Figure 8, sourced from Nationaal Perspectief Energie en Ruimte) note a total energy (including, but not limited to electricity) consumption for 2015 of 3087 PJ, including losses. Realising a 25% reduction in energy consumption and a 45% reduction in conversion and transport losses, energy demand for 2050 is anticipated to be 2165 PJ. The total useful consumption (i.e., excluding losses) is 1776 PJ.

Berenschot (review) – Den Ouden, Lintmeijer, Bianchi & Warnaars (2018)
Den Ouden, Lintmeijer, Bianchi & Warnaars (2018) have reviewed a host of *systeemverkenningen*, including such efforts by RLI, Gasunie, Berenschot, PBL, KIVI, CE Delft and others, which have been published between 2014 and 2018 and look ahead to the Dutch energy system in 2030 and/or 2050.

For 2050, these reports anticipate a total energy mix spanning between 1145 and 1471 PJ. Some reports see limited use of fossil fuels (oil, coal, natural gas) and in most, more than half of the energy mix (552 to 1134 PJ) is formed by electricity and/or hydrogen (produced using electrolysis[21]). At least, these reports anticipate a contribution to the total energy mix of electricity (for final use) of 352 to 478 PJ and (mixed) hydrogen of 8 to 182 PJ. Following footnote 21, the total electricity and green hydrogen use in these scenarios ranges from 356 to 569 PJ.

These findings were used as a basis for two scenarios in 2050: one focused on domestic energy production and large-scale electrification; the other based on import of feedstock (biomass and hydrogen). In the former, the total energy mix is 1013 PJ, of which 553 PJ (55%) is electricity and 214 PJ (21%) is hydrogen – of which 95% is produced using electrolysers (i.e., green hydrogen). In the latter scenario, the total energy mix is 1158 PJ, of which 425 PJ (37%) is electricity and 272 PJ (23%) is hydrogen. In this scenario, the hydrogen is produced using steam-methane reforming and thereby is blue or grey. Combined electricity and green hydrogen usage ranges from 425 to 757 PJ.

International aviation and shipping do not seem to be considered.

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[21] Hydrogen that is explicitly indicated as 'blue' hydrogen is excluded from these figures. In case a particular energy quantity includes blue as well as green hydrogen, a 50/50-share is assumed, and only the share of green hydrogen is reported. Blue hydrogen is included in the energy values for the total energy mix.

Berenschot and Kalavasta, in support of the 'Integrale infrastructuurverkenning' – den Ouden et al. (2020)

Den Ouden et al. (2020) have developed four CO_2-neutral scenarios, which mostly differ in the geographical level at which the energy transition is shaped (regional, national, European or global). Production of sustainable aviation fuels are included in all scenarios, but in none of these, domestic production satisfies demand.

Total energy demand (excluding synthetic bunker fuels for IAS as well as non-energy use[22]) varies between 1181 and 1735 PJ. Consistent with other scenarios, electricity makes up approximately 50% or more. In case non-energy use is included, these numbers grow to 1567 to 2526 PJ. The total supply required to cover these demands ranges from 1775 to 2964 PJ, indicating losses of 12% to 15%. Of these totals, between 510 and 1232 PJ is renewable electricity.

Electricity production from renewable sources (wind, solar and hydrogen[23]) ranges between 760 and 1426 PJ (211 – 396 TWh).

Synthesis

Table 18 summarises the results presented in this section and shows total energy and electricity demand in the Netherlands in 2050. All figures are final consumption values and thereby exclude losses in the process between production and use.

Table 18: Summarised results of anticipated domestic energy and electricity demand (excluding bunker fuels) in the Netherlands in 2050

Source	Energy [PJ]	Electricity [PJ]	Remarks
Kuijers et al. (2018)	1776		
Den Ouden et al. (2018) – review (range)	1145 – 1471	552 – 1134	Electricity including green hydrogen production, excluding synthetic bunker fuels[24]
Den Ouden et al. (2018) – review (minima)		356 – 569	
Den Ouden et al. (2018) – scenarios	1013 – 1158	425 – 757	
Den Ouden et al. (2020)	1181 – 1735	510 – 1232	Excluding synthetic bunkers from addn. wind at sea

Energy demand values range from 1013 to 1776 PJ. Electricity demand is anticipated between 356 and 1232 PJ. Averaged, total energy demand is slightly over 1400 PJ, of which slightly less than 700 PJ is formed by electricity and (green) hydrogen.

Kuijers et al. (2018) and den Ouden et al. (2020) anticipated losses to be equal to 18% and 33 to 41% (relative to availability). As such, energy and electricity production output should be 18 to 41% higher than the consumption values shown in Table 18.

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[22] In case energy carriers are used for non-energy purposes, the energy carriers are a production feedstock to a (chemical) process. In this case, the energy content is not used to power the production process, but is left contained in the product (CBS, 2011). A well-known example of non-energy use is the use of oil in the production of plastics.

[23] It is assumed hydrogen is used to store renewable electricity when supply exceeds demand. As such, it becomes a renewable energy source.

[24] Following footnote 21, hydrogen use is as much as possible limited to green hydrogen. It is in any case assumed hydrogen is produced for domestic use or international trading and not as feedstock for the production of synthetic bunker fuels.

4.2.4 Availability for e-fuels for aviation

In Section 4.2.2, various ranges for the potential for renewable electricity generation were found. The theoretical potential was established to range from 2814 to 3669 PJ and the realistic potential to lie between 2184 PJ and 2869 PJ. Estimating losses based on Kuijers et al. (2018) at 25%[25], this yields usable potentials of 2111 to 2752 PJ (theoretical) and 1638 to 2152 PJ (realistic). Table 19 summarises the resulting differences between demand (first column) and supply (second column), the latter soured from Section 4.2.3.

Table 19: Difference between anticipated domestic electricity demand and potential for renewable electricity production in the Netherlands in 2050

Electricity demand [PJ]	Electricity supply [PJ], including 25% losses	Difference [PJ]
Lower: 356	Theoretical, lower: 2111	1755
Lower: 356	Theoretical, upper: 2752	2396
Upper: 1232	Theoretical, lower: 2111	879
Upper: 1232	Theoretical, upper: 2752	1520
Lower: 356	Realistic, lower: 1638	1282
Lower: 356	Realistic, upper: 2152	1796
Upper: 1232	Realistic, lower: 1638	406
Upper: 1232	Realistic, upper: 2152	920

Depending on the scenario, a difference between domestic electricity demand and supply of 406 to 2396 PJ is found (average: 1369 PJ). Limiting this to the realistic range of renewable electricity production, the excess supply is 406 to 1796 PJ (average: 1101 PJ). This is the amount of renewable electricity that is potentially available for the production of e-fuels for aviation.

Additional electricity generation by wind at sea, based on Berenschot and Kalavasta – den Ouden et al. (2020)

In addition to the analysis presented here, den Ouden et al. (2020) have analysed the potential additional electricity generation for synthetic bunker fuels for use by international aviation and shipping[26]. To this extent, they have assumed a 40% increase in anticipated installed wind power at sea. 40% was chosen because it would allow wind at sea power in the "national" scenario that already included highest installed power (52 GW) to increase up to the theoretical lower value estimated by Kuijers et al. (2018), being 72 GW[27]. This would yield an increase in renewable electricity production would increase of 179 to 334 PJ (50 – 93 TWh).

In addition to analysing the yield from increasing installed wind power at sea by 40%, a number of similar analyses can be made:

1. Increasing installed wind power at sea to the upper realistic value (54 GW) across the board. This will make little difference for the "national" scenario (in which 52 GW is planned), but has a larger impact for other scenarios. Depending on the scenario considered, wind power is increased by 2 to 26 GW (4 to 93%), delivering an increasing in produced electricity 32 to 415 PJ, compared to the baseline scenario without any additional electricity production.
2. Increasing installed wind power at sea to the lower theoretical value (72 GW) across the board. This will not make a difference for the "national" scenario, but will yield a higher increase in other scenarios. Specifically, an additional amount of 334 to 701 PJ of electricity would be produced. Depending on the scenario, installed wind power would rise by 40 to almost 160%.

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[25] More than what is assumed by Kuijers et al. (2018), but still a notable improvement over the current situation.

[26] Den Ouden et al. (2020) themselves propose to utilise the additional energy for the production of synthetic bunker fuels. Nevertheless, it can of course also be used to meet other demand, or to be exported.

[27] This is 50% higher than the realistic upper value assumed by Kuijers et al. (2018), equal to 54 GW.

3. Increasing installed wind power at sea by 110%, such that the capacity in the “national” scenario grows to the upper theoretical limit of 108 GW. In this case, between 491 and 919 PJ of additional electricity would be produced, compared to the baseline.
4. Increasing installed wind power at sea to the upper theoretical value across the board. This option is similar to option 1, but will increase power to 108 GW (rather than to 72 GW). This is an increase of 110 to 279%, delivering an additional amount of electricity of 919 to 1244 PJ compared to the baseline.

Table 20 provides an overview of the results.

Table 20: Additional electricity production from wind at sea

Option	Additional electricity production [PJ]	Remarks
1	32 – 415 (average: 302)	Based on upper realistic value
2	334 – 701 (average: 596)	Based on lower theoretical value
3	491 – 919 (average: 625)	
4	919 – 1244 (average: 1153)	Based on upper theoretical value

In evaluating the results based on the theoretical potential identified by Kuijers et al. (2018), it is important to emphasise a number of their remarks regarding these theoretical limits. Whereas these do take into account protected areas and the interests of international shipping, they do not take into account those of other stakeholders in the North Sea (including fishery). Furthermore, the it does not take into account the area required for wind regeneration.

Additional electricity generation from solar, based on Berenschot and Kalavasta – den Ouden et al. (2020)

Whereas den Ouden et al. (2020) look to increased wind power at sea to yield additional electricity generation that can be used for the production of synthetic bunkers, a similar analysis can be made for solar-PV. For domestic use, den Ouden et al. (2020, p. 41) estimate a production of 162 to 392 PJ from solar-PV. Comparing with data from Kuijers et al. (2018), presented in Table 17, shows the total potential for solar energy ranges between 702 and 1117 PJ (realistic) or between 812 and 1167 PJ (theoretical).

Taking a similar approach as for wind at sea, solar power is estimated to be increased in various ways:

1. Increasing solar production to lower realistic potential (702 PJ, 608 PJ when efficiency-corrected[28])
2. Increasing solar production to upper realistic potential (1117 PJ, 968 PJ when efficiency-corrected[28])
3. Increasing solar production to lower theoretical potential (812 PJ, 659 PJ when efficiency-corrected[28])
4. Increasing solar production to upper theoretical potential (1167 PJ, 934 PJ when efficiency-corrected[28])

This yields the figures presented in Table 21.

Table 21: Additional electricity production from solar

Option	Additional electricity production [PJ]	Remarks
1	216 – 425 (average: 340)	Based on lower realistic value
2	576 – 806 (average: 700)	Based on upper realistic value
3	257 – 488 (average: 381)	Based on lower theoretical value
4	541 – 772 (average: 665)	Based on upper theoretical value

Overview

Combining the data presented in this section yields the overview presented in Table 22.

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[28] As indicated in Section 4.2.2, Kuijers et al. (2018) assume a 26% and a 30% efficiency in their realistic and theoretical estimates, respectively. Den Ouden et al. (2020, footnote 8, p. 39) use 24%. Correction factors (of 24/26 = 0.92 or 24/30 = 0.80) have been applied to ensure consistency.

Table 22: Availability of renewable electricity in the Netherlands in 2050 for the production of e-fuels for aviation

Method	Data	Energy sources	Additional electricity production [PJ]	
			Realistic	Theoretical
Own analysis	Table 19	All: wind at sea, wind on land, solar, water, geothermal	406 – 1796 (avg: 1101)	879 – 2396 (avg: 1638)
Based on den Ouden et al. (2020)	Table 20	Wind at sea	32 – 415 (avg: 302)	334 – 1244 (avg: 791)
	Table 21	Solar	216 – 806 (avg: 520)	257 – 772 (avg: 523)

As indicated in the table, the analysis based on den Ouden et al. (2020) is limited to additional electricity generation through increased wind at sea and solar capacity. The 'bottom-up' analysis presented at the beginning of this section also takes wind on land, water and geothermal power into account. As Table 17 shows, however, wind at sea and solar power yield greatest potential. This can also be inferred from noting the combined additional electricity production from wind at sea and solar (sum of last two rows of Table 22) form the largest share of the additional electricity production from all energy sources (first row of Table 22).

4.3 Conversion of NL available renewable electricity for e-fuels for aviation to available SAF

4.3.1 Methodology

As shown in Figure 4, renewable electricity is required for all steps of synthetic fuel production, including the production of hydrogen and carbon dioxide from abundantly available primary resources. The assumption is made in this chapter that water will be available in sufficient quantities (this assumption is examined in Appendix A) and availability of carbon dioxide will not be limiting (availability of ambient air for DAC will not be limiting in any scenario and the availability of recycled carbon in the Netherlands is examined in Appendix B). For this reason, this report approximates the potential to produce synthetic jet fuel in the Netherlands based on availability of renewable electricity in 2050, as calculated in Section 4.2.4. Efficiency factors for production of jet fuel from electricity based two previous works are applied, to present a range for the amount of synthetic jet fuel that the Netherlands could produce in 2050.

4.3.2 Conversion factors from previous work

Power-to-Liquids - Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel – Bauhaus Luftfart for German Environment Agency (2016)
This paper was commissioned by the German Environment Agency to explore the potential of power-to-liquid as a fuel supply. Power to Liquid production pathways and the drop-in capability of the resulting jet fuel are explained and their comparative performances are discussed in terms of greenhouse gas emissions, energy efficiencies, costs, water demand and land requirements.

In Table 4 and 5 of Bauhaus (2016), techno-economical parameters for production of PtL fuels are presented, for low and high temperature electrolysis respectively. For low temperature electrolysis, energy efficiency of the conversion of electricity to fuel is 43% when direct air capture is applied and 53% when recycled carbon is applied. For high temperature electrolysis, these efficiencies are 47% and 64% (Bauhaus Luftfart, 2016).

Hydrogen-powered aviation - A fact-based study of hydrogen technology, economics, and climate impact by 2050 – McKinsey & Company for the Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU (2020)
This research, which was performed by McKinsey and Company for the European Commission's Clean Sky 2 and Fuel Cells and Hydrogen 2 Joint Undertakings, quantifies and describes technological, economical and climate-related aspects of hydrogen as a fuel, in order to advocate feasibility of hydrogen as a sustainable and scalable solution to decarbonise aviation.

In Chapter 3 (exhibit 15), the comparison is made between the energy efficiency of producing hydrogen for direct use as a fuel from renewable electricity, and the energy efficiency of producing synthetic jet fuel from renewable electricity with hydrogen as an intermediate. The results are 22% energy efficiency when direct air capture is used to provide carbon dioxide, and 35% energy efficiency when recycled carbon is used to provide carbon dioxide (for production of hydrogen, energy efficiency is estimated at 58%) (McKinsey & Company, 2020).

4.3.3 Potential for the Netherlands to produce synthetic fuel in 2050

In order to approximate the potential to produce e-fuels in the Netherlands via direct air capture or recycled carbon, results from both aforementioned studies are combined to averaged efficiency figures. For DAC, this value is determined as 37%, and for recycled carbon, an efficiency of 51% is assumed. The results are shown in Table 25.

Table 23: Availability of synthetic aviation fuel in the Netherlands in 2050

Energy sources and method	**Available renewable electricity [PJ]**		**Available SAF [PJ]**	
			DAC (37 %)	**Recycled carbon (51%)**
All (wind at sea, wind on land, solar, water, geothermal) through own analysis	Realistic	406 – 1796 (avg: 1011)	150 – 665 (avg: 407)	207 – 916 (avg: 562)
	Theoretical	879 – 2396 (avg: 1638)	325 – 887 (avg: 606)	448 – 1222 (avg: 835)
Wind at sea, based on den Ouden et al. (2020)	Realistic	32 – 415 (avg: 302)	12 – 154 (avg: 112)	16 – 212 (avg: 154)
	Theoretical	334 – 1244 (avg: 791)	124 – 460 (avg: 293)	170 – 634 (avg: 403)
Solar, based on den Ouden et al. (2020)	Realistic	216 – 806 (avg: 520)	80 – 298 (avg: 192)	110 – 411 (avg: 265)
	Theoretical	257 – 772 (avg: 523)	95 – 286 (avg: 194)	131 – 394 (avg: 267)

For realistic[29] amounts of available renewable electricity, average SAF availability is estimated to range from 112 to 407 PJ (average: 237 PJ) for PtL based on direct air capture (and a lower efficiency of 37%) and is estimated to range from 154 to 562 PJ (average: 327 PJ) when recycled carbon is used (achieving a higher efficiency of 51%). In terms of megatonnes of SAF (using an energy density of 43.5 MJ/kg), the realistic amount of synthetic fuel that can be produced in the Netherlands varies between 2.6 and 9.3 Mt (average: 5.4 Mt) based on DAC and from 3.5 to 12.9 Mt (average: 7.5 Mt) using recycled carbon.

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[29] Based on the classification by Kuijers et al. (2018).

5 Overview of SAF availability in relation to demand

This chapter compares the previously established figures on (bio- and e-fuel) SAF availability determined in Sections 3.4 and 4.3 with the demand scenarios presented in Section 2.4 (varying in estimated growth based on WLO-scenarios and the utilisation of alternative propulsion)[30]. The results of this comparison are shown in Table 24. For e-fuels, only realistic[29] amounts of available renewable electricity are used. For SAF demand, discounts for possibly alternatively propelled aircraft are not applied[31].

Table 24: Availability of sustainable aviation fuel in the Netherlands in 2050 in relation to demand scenarios presented in Table 3

Availability		% demand covered		
SAF type and scenario	**Value [PJ]**	**WLO Low (214 PJ)**	**WLO High (241 PJ)**	**High-Tech (222 PJ)**
Biofuel, NL resources	35	16	15	16
Biofuel, EU resources	332	155	138	150
E-fuel, NL resources (realistic), DAC	237	111	98	107
E-fuel, NL resources (realistic), recycled carbon	327	153	136	147

Table 24 readily shows the amount of biofuel resources in the Netherlands can only supply a small portion (15 to 16%, depending on the scenario) of demand for aviation fuel. In case the Netherlands is able to acquire through trading a ‘fair share’[32] of biofuel feedstocks from other countries, 138 to 155% of Dutch demand for international aviation fuel can be met. The energy requirements of feedstock transportation are not accounted for in these figures.

Thanks to a notable potential for generating renewable electricity in the Netherlands (especially using wind at sea and solar energy), Dutch renewable energy resources used for the production of e-fuels are estimated to cover the demand for aviation fuel in all but one scenarios, with margins ranging from -2% to 53%. Using recycled carbon results in a higher efficiency – and therefore a higher amount of SAF produced – compared to using DAC.

In case not all available feedstocks are allocated to the aviation sector (as was discussed in Section 2.5), the availability of sustainable aviation fuels reduces and can support a share of the total demand. Given the uncertainty related to feedstock allocation, it is difficult to comment on a realistic value. The fact that (for e-fuels) only excess renewable electricity was studied here, however, is supportive of (but not guarantees) the assumption that it is completely available for the aviation sector.

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[30] As indicated in Section 2.4, these scenarios do not take into account the effects of possible cost and price changes due to the (increased) use of SAF on demand.

[31] Although it is not unlikely for alternatively propelled aircraft to change SAF demand, the impact on total aviation energy demand will be lower. Put differently: in case battery- or hybrid-electric are commonplace in 2050, these will use a part of the renewable electricity currently estimated to be available for the production of e-fuels.

[32] Determined based on the share of international aviation fuel used in the Netherlands compared to EU27, as indicated in Table 11.

6 Conclusions

The combined results of this research, culminating in an estimate of the amount of SAF which could be produced in the Netherlands in 2050 from various feedstocks relative to demand, are shown in Figure 7. As indicated in Section 2.5, there is large uncertainty about the amount of feedstocks available for (or: allocated to) the aviation sector. As such, the figure shows two scenario's, in which 20% or 100% of feedstocks is allocated to aviation.

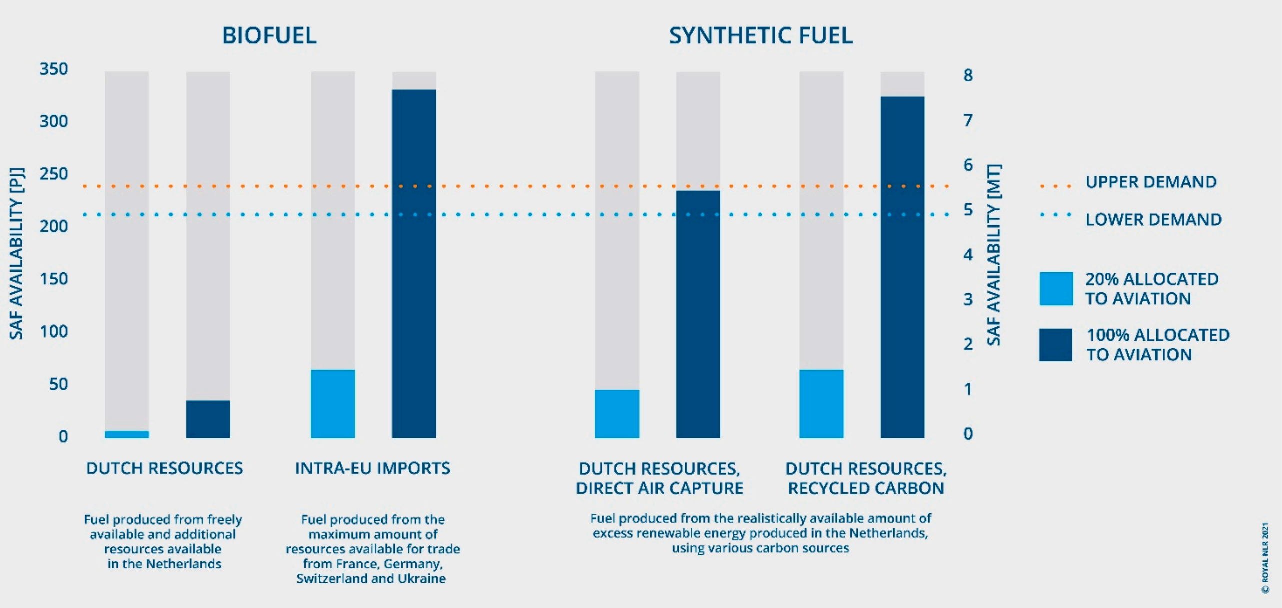

Figure 7: SAF potential for the Netherlands in 2050 based on feedstock availability

It can be inferred from Figure 7 that feedstocks of organic origin purchased from European countries and e-fuels are the most promising feedstocks for SAF in the Netherlands. It also highlights that if feedstock availability to the aviation sector is substantially lower than 100%, even these most promising sources might not be able to cover the aviation fuel demand. The minimum share that needs to be allocated to aviation differs per feedstock.

The availability of feedstocks for biofuels in the Netherlands in 2050 is expected to be far lower than the range of demand for aviation. Even this number of 35 PJ may be too optimistic, as other industries than aviation may claim these freely available and additional resources. Based upon a proportionate fraction of the excess biomass that France, Sweden, Germany and Ukraine are expected to have in 2050, it seems that trade within the EU could cover the national deficit. However, sustainability of transporting feedstocks, dependency on other countries for fuel and willingness of those countries to trade must be taken into account. Therefore, this option is less desirable than national production, but can be fallen back upon if necessary to achieve climate targets. In this case, as neighbour countries of the Netherlands, Germany and France are most likely the most logical trade partners.

If the forecasted excess renewable electricity available in the Netherlands in 2050 is allocated to production of synthetic fuels for aviation, demand could be fully met. This holds for production of synthetic fuels both via direct air capture and recycled carbon. Direct air capture would be more sustainable, whilst recycled carbon would leave more renewable electricity for other industries. Whether excess renewable electricity will be available to aviation is not yet clear. In order to obtain a reliable forecast of the availability of SAF for aviation, future allocation of renewable energy, specifically biomass and renewable electricity, must be addressed. Until this is done, results must be interpreted cautiously.

7 Recommendations

This section lists recommendations, that follow from the results and conclusions obtained in this study. Section 7.1 lists recommendations for further research, whereas Section 7.2 is concerned with advice on policymaking.

The recommendations listed are those that fit in the scope of this research (detailed in Section 1.2): the technical availability of SAF. A number of other aspects provide relevant research or policy questions (e.g. suitability of particular feedstocks for particular geographical areas, biodiversity, etc.), but are left for other publications to identify. Similarly, other opportunities to reduce CO_2 emissions from aviation (such as energy efficiency improvements, which are taken into account in the demand scenarios in Section 2.4) are not listed. Van der Sman et al. (2021) provides an extensive overview of decarbonisation measures besides the use of SAF.

7.1 For further research

As mentioned in Section 1.1, a sub objective of this research is to identify where further research is needed to fully comprehend the role of SAF in sustainable aviation to make informed policy decisions. The following recommendations have been formulated:

- More detailed insight in SAF-demand specific to the Dutch situation through a scenario-based analysis of demand for different energy carriers in the Netherlands; this would follow from several scenarios for fleet composition and air traffic activity. This research would include the impact of alternative propulsion methods on (renewable electricity) demand.
- An analysis of cost / price / investment of different routes towards SAF production for the Netherlands. This would include roadmapping towards 2030 and 2050: what feedstocks and technologies will be available in intermediate years, how quickly can things be deployed and subsequently scaled up? This could include production locations, infrastructure, etc.
- An exploration of several scenarios for feedstock allocation over various industries in the Netherlands. Alternatively or in conjunction, collaboration with (researchers from) other sectors can help to model the entirety of the Netherlands as an energy (and resource) system. Balancing all interests can subsequently shed light on the share of feedstock allocation to the aviation sector is realistic.
- More detailed analysis of expected efficiency of carbon capture (DAC versus point sources, depending on pollution of exhaust stream) and an analysis of environmental impact of using DAC.
- Availability of recycled carbon for aviation, for example which rest-streams are already utilised (e.g. by agriculture) and which rest-streams are suitable for carbon capture.
- An investigation of seasonal effects in resource/feedstock availability (e.g. renewable energy), production capacity and demand.
- Technical, sustainable and economical potential of trade with other European countries, notably France, Germany, Sweden and Ukraine. This should investigate both the trading of feedstock (for SAF-production in the Netherlands) and the trading of SAF (produced in a different country, reducing feedstock transport and associated energy demand and emissions).

7.2 For policymaking

The analyses presented in this report and the conclusions drawn in Chapter 6 give rise to a number of recommendations for policymaking. First of all, this concerns the potential and need for SAF production and deployment in the Netherlands. Second, and taking a wider perspective, this concerns the position of aviation energy demand in national energy planning. Given the 2050-timeframe of this study, recommendations for policymaking focus on the longer term.

Concerning potential and need for SAF production and deployment

Whereas commercial production of bio-based SAF is most promising in the short term, this research shows that freely available Dutch feedstocks can only contribute a small portion of total anticipated drop-in SAF demand. As increases in SAF-uptake are necessary for reducing the carbon footprint of commercial aviation (noted, for example, by van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), current Dutch developments in the field of bio-based SAF are commendable steps that the authors expect will make an important contribution to the 14% uptake target set by the Ministry of Infrastructure and Water Management for 2030. Trading with other EU-countries – notably France, Germany, Sweden and Ukraine – could provide further feedstock supply, which would enable larger bio-based SAF production, or direct import of SAF for use by aircraft departing the Netherlands.

For the longer-term, reliance on bio-based fuels produced from domestic or internationally sourced feedstocks has important limitations and risks. As other countries are also faced with the challenge of decarbonising aviation, trade potential might be limited. Moreover, trade potential might fluctuate, and reliance on trading increases the energy dependence of the Dutch aviation sector on other countries. Combining these observations with the promise of the production of e-fuels based on Dutch feedstock, it is recommended the Netherlands pursues a leading position in e-fuels production. This utilises the potential for renewable electricity generation, notably from wind at sea, as well as the knowledge and capabilities that exists in this field – as for example demonstrated by the recent worldwide first flight on synthetic kerosene, produced in the Netherlands (Government of the Netherlands, 2021). Moreover, this connects well to regional developments of green hydrogen production, such as in the Groningen province (Provincie Groningen, 2020; New Energy Coalition, 2021), in the North Sea Canal area (Government of the Netherlands, 2021) and in the southwestern part of the Netherlands (Hydrogen Valleys, n.d.). Realising this leading position in e-fuels production and development can be supported by a number of policies, actions and efforts:

- Focused on supply:
    - Stimulating the availability of (green) hydrogen and captured CO_2, using for example direct air capture, carbon recycling, or other techniques. This first of all requires knowledge development, followed by the support for pilot plants and possible stimuli towards industrial scale-up. This is already part of the 'Uitvoeringsagenda Biogrondstoffen' (van Veldhoven - van der Meer & Wiebes, 2020), but might receive more emphasis given the opportunity identified by this research.
    - Guarantee the availability of sufficient renewable electricity, required for the production of green hydrogen and CO_2 capture.
- Focused on demand and uptake:
    - Working towards the development of an international (European or global) mandate or sub-mandate for synthetic kerosene, thereby strengthening the commercial business case of this type of SAF. Currently proposed mandates (as well as non-binding targets), such as in the aforementioned 'Uitvoeringsagenda Biogrondstoffen' do not distinguish between bio-based and synthetic SAF, thereby risking lock-in to (resource-constrained) bio-based SAF.
    - Stimulating the use of synthetic kerosene, as proposed in the 'Uitvoeringsagenda Biogrondstoffen'.

Concerning the position of aviation energy demand in national energy planning

None of the studies on future energy demand in the Netherlands reviewed in this report explicitly take into account energy demand of international aviation. Whereas it is understandable that research focuses on energy uses and associated emissions that are covered by the Paris Agreement, long-term energy planning should recognise sectors outside that domain. Numerous studies, showing the crucial role of SAF in general and synthetic fuels in particular in decarbonising aviation, further emphasise this need (Energy Transitions Committee, 2018; van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Moreover, as energy use in other sectors decreases (or: grows less rapidly), the portion of aviation-related energy consumption compared to the total energy consumption in the Netherlands will increase. This is illustrated in the following box.

> **AVIATION ENERGY USE AS PART OF TOTAL DUTCH ENERGY USE**
> The CBS energy balance (2020) shows the total use of energy by the energy sector and by final use in 2019 was approximately 3000 PJ. Bunker fuels for aviation and maritime uses in that same year totalled almost 640 PJ, of which 166 PJ by international aviation (CBS, 2021). As such, the share of aviation energy was (166 / [3000 + 640] =) 4.5%.
>
> For 2050, aviation energy demand is foreseen to range between 214 and 241 PJ (based on Table 3), or 226 PJ on average, whereas Section 4.2.3 shows total energy demand to reach 1400 PJ. Assuming an unchanged demand for energy by the maritime sector (of 474 PJ), the aviation share by 2050 would reach (226 / [1400 + 226 + 474] =) 10.7%. This is more than double the share in 2019.

Besides the recommendations for further detailing long-term aviation energy demand scenarios already made in Section 7.1, also taking into account possible political prioritisation of sectors (as discussed briefly in Section 2.5), all related ministries and departments of the Government of the Netherlands should cooperate to ensure the aviation energy demand is accounted for[33]. Primary roles are foreseen for the Ministries of Infrastructure and Water Management and Economic Affairs and Climate Policy. The current research shows that opportunities exist (notably by installing additional wind power at sea), but also indicates that these are currently not planned for. Earlier errors or omissions, such as failing to take into account the renewable electricity demand for envisioned Dutch hydrogen production brought to light in 2020 (van Santen, 2020), show this cooperation and reconciliation does not happen by itself, but requires deliberate action.

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[33] Ideally, the energy demand of the aviation sector should be considered in a holistic system-view that encompasses the totality of (sustainable) energy demand, by all sectors and industries in the Netherlands. Such a system-view can help the Government conduct long-term energy planning, balance interests and – if and when relevant – incentivise actors.

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Appendix A Availability of water for hydrolysis

In order to produce hydrogen by electrolysis, water and renewable electricity are needed as a primary resources. Whilst projections of availability of renewable electricity are generally used to calculate future availability of hydrogen, it may well be that water will become the actual limiting factor, as fresh water resources in the Netherlands are expected to become scarce in the future (Ministry of Housing, Spatial Planning and the Environment, 2009). The main reasons for this are (Ministry of Infrastructure and the Environment, and Ministry of Economic Affairs, Agriculture and Innovation, 2012):

- a shortfall on water available from rivers and canals;
- excess demand on reserves, or reserves exhausted (IJsselmeer);
- accelerated salinization of intake points (below the major rivers: Gouda and Bernisse);
- groundwater levels on the higher sandy grounds are sinking and water supply from the main water system is hardly possible; and
- salination of parts of the southwest estuary area and water supply from the main water system is hardly possible.

Of course, fresh water is needed for many more applications than producing hydrogen, such as human consumption, agriculture, food production and cooling. Therefore, hydrogen production is not expected to be prioritised. Additional fresh water could always be supplied by desalination of saline or brackish waters, but this technology is notoriously energy intensive and would increase the energy demand for hydrogen production significantly.

In order to fully understand when and to which extent this will become an issue, additional research which examines the availability of fresh water for hydrolysis is recommended.

Appendix B Availability of recycled carbon in the Netherlands

Of the companies in the Netherlands to which ETS is applicable, 85% of carbon emissions are caused by 10% or the companies. (EBN & Gasunie, 2017) All ETS locations emitting more than 100,000 tonnes of CO2 per year are shown in Figure 8. It can be seen that most of these locations are situated around the harbour areas in the Zuid Holland and Noord Holland districts, the harbour area in the south of the Zeeland district and up north at the top of Groningen. This grouping of CO_2 point sources makes carbon recycling more feasible and cost efficient; as a synthetic fuel plant could be constructed in close proximity to several intensive carbon emitting plants.

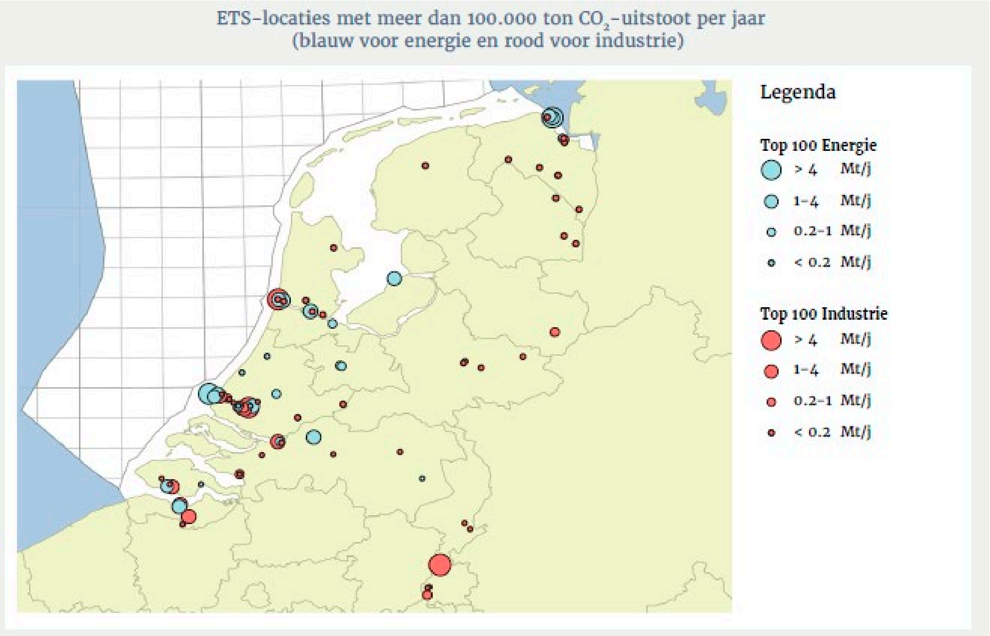

Figure 8: Point sources in the Netherlands emitting >100,000 tonnes CO2 per year (figure from EBN & Gasunie, 2017)

CO_2 point sources in the Netherlands are often divided into industrial and energy generation sources, according to which they are also colour coded in Figure 8. The amount of CO_2 emitted by the top 10 industrial- and energy generation point sources is shown in Table 25.

Table 25: CO_2 industry and energy generation point sources in the Netherlands

Top 10 Industry CO_2 sources (Mt/year in 2016)		**Top 10 Energy generation CO_2 sources (Mt/year in 2016)**	
Tata Steel	6.21	RWE Eemshaven	8.32
Chemelot	4.79	Uniper Centrale Maasvlakte	5.95
Shell Raffinaderij	4.25	Uniper Centrale Maasvlakte 3	4.67
Yara Sluiskil	3.73	Nuon Centrale Hemweg	4.0
Dow Benelux Zeeland	2.74	Nuon Power Velsen	3.63
Shell Moerdijk chemie	2.55	Essent Amercentrale	3.52
BP Raffinaderij	2.29	ENGIE Centrale Rotterdam	3.19
Esso Raffinaderij	2.10	ENGIE Eemscentrale	2.21
Zeeland Raffinaderij	1.55	NUON Power IJmond	2.15
Guvnor Petroleum Rotterdam	0.42	Sloecentrale Zeeland	1.42
Total	**30.63**	**Total**	**39.06**
Next 10 industry sources	3.0	Next 10 Energy sources	10.0

For the analysis of available recycled carbon, a scenario is considered in which four synthetic fuel plants are built in the four locations which have the most CO_2 point sources nearby (under 25 km radius). Based upon the assumption that 90% of carbon emitted in 2016 can be allocated to fuel production, the amount of carbon which would be available in every location has been calculated. Assuming 60% carbon conversion, and an average of 3.25 kg CO_2 being required for every kg of kerosene (Shell, 2018), the theoretical amount of synthetic kerosene which could be produced if carbon is the limiting factor is listed below.

Rotterdam Port Area:	22.88 Mt CO_2/year, yielding 7.04 Mt kerosene available
IJmuiden:	17.56 Mt CO_2/year, yielding 5.40 Mt kerosene available
Delfshaven:	9.48 Mt CO_2/year, yielding 2.92 Mt kerosene available
Terneuzen:	8.50 Mt CO_2/year, yielding 2.62 Mt kerosene available

As Schiphol's kerosene demand in 2019 was 3.4Mt (calculation method from Terwel & Kerkhoven used on 2019 data from CBS (2021)), it can be seen that industrial and energy generation exhaust streams from the Rotterdam Port Area or IJmuiden would provide more than enough CO_2 to serve Schiphol Airport.

Appendix C Demand for carbon via DAC

Theoretically, a great amount of carbon is available via DAC; namely all the carbon in the atmosphere. Practically, this is not the case, as direct air capture requires space and energy input, and needs a useful application to be economical. For this reason, it is expected that demand from industry based on cost competitiveness and external pressure to decarbonize, and not technological readiness, will drive DAC capacity in the Netherlands. (Terwel & Kerkhoven, 2018) Therefore, in the calculation of available carbon via DAC, predicted demand has been used as an indication of DAC availability.

Fasihi, Efimova, & Breyer (2019) use a calculation on data from over 10 scientific papers to predict DAC demand in several industries from 2020 – 2050. In their calculation, they take into account the predicted price of DAC at various time points in the future. They also consider demand for DAC in CO_2 abatement, but this will not be applied in this report as the focus is resources for sustainable aviation fuels.

A row has been added to the data of Fasihi et al which roughly predicts DAC demand in the Netherlands. Using 2018 statistics from CBS (NL) and ICAO (global), commercial flight movements including freight to and from the Netherlands were calculated to be around 1.74% of global flight movements. This percentage was used to convert the global aviation sector DAC demand to the Netherlands aviation sector DAC demand. This conversion could be on the conservative side, as the Netherlands are situated in Europe and have committed to reducing emissions, are proud to have a “knowledge economy” and are home to several DAC and synthetic fuel start-ups. Assuming that availability of hydrogen and renewable energy are not limiting, the amount of sustainable kerosene (SAF) which can be made from the DAC created carbon is given in the table. As a conversion factor, 3.25 kg CO2 required per kg synthetic fuel was used. (Shell, 2018)

Table 26: Predicted DAC demand in 2050 (data from Fasihi, Efimova, & Breyer (2019))

	2050
Total demand (Mt CO_2/year)	7144
Aviation industry demand (Mt CO_2/year)	1543
NL aviation industry demand (Mt CO_2/year)	26.8
NL demand SAF from DAC carbon (Mt SAF/year)	**8.3**

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