Master thesis

Bio-SAF vs. e-SAF: land-use efficiency of conversion routes for sustainable aviation fuel production in the EU

A land-use comparison of SAF production routes using biomass, renewable hydrogen and direct air capture

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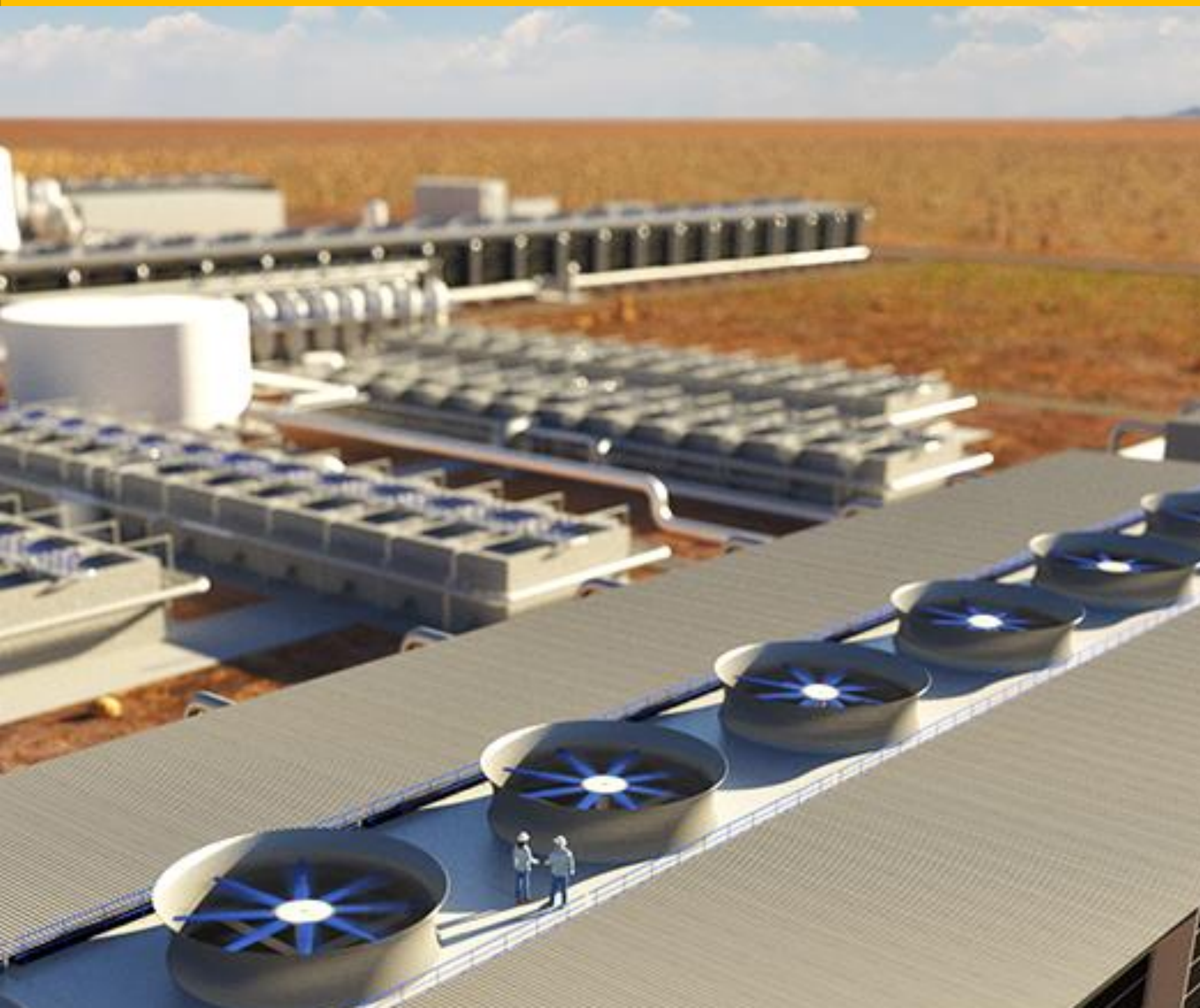

Abstract

The aviation sector is difficult to de-fossilize, with few alternatives to fossil jet fuel. The two alternatives that show the highest potential are sustainable air fuel (SAF) produced from either biomass or from CO_2 derived from direct air capture (DAC) and renewable hydrogen. However, bio-based SAF (bio-SAF) and electro-SAF (e-SAF) both require substantially more land compared to the production of conventional jet fuel, as fossil sources have higher energy densities than biomass or renewable electricity. The current body of literature on sustainable aviation is missing an extensive land use comparison between bio-SAF and e-SAF production routes, while land use is an important environmental indicator of the energy sector. This research aims to fill that gap, by constructing a model which includes all necessary chemical conversions and maps the required utilities such as hydrogen, electricity and heat. The included routes are hydro-processed esters and fatty acids (HEFA), alcohol to jet (AtJ), biomass to liquid (BtL), CO_2 hydrogenation and methanol upgrading (e-MeOH) and CO_2 upgrading to SAF through Fischer-Tropsch synthesis (e-FT). Land should be used as efficiently as possible, so hybrid solar & wind farms and combinations of bio-SAF and e-SAF production are examined in this research.

The results show that e-SAF production uses 10 – 20 times less land compared to bio-SAF for the same amount of fuel production. This is mainly due to biomass harvests only taking place once a year, while CO_2 capture and electricity production can take place continuously. However, e-SAF production requires 5 – 30 times as much electricity due to the large hydrogen demand, energy consumption of DAC and heat supply. As electricity is also becoming a scarcer resource, the trade-off between land and electricity requirements needs to be made for the production of SAF. It is expected that bio-SAF routes are a viable alternative to fossil jet fuel the next few decades as they are further in development and have lower costs compared to e-SAF. E-SAF routes are expected to be the better option towards 2050 when DAC and electrolyzers are further developed, costs have decreased and renewable electricity is more abundantly available. Combined routes are also an alternative, as electricity requirements are lower compared to individual e-SAF routes in exchange for slightly higher land use.

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1. Introduction

1.1. Societal background

The European Union (EU) is making significant efforts to de-fossilize all sectors in order to limit global warming to 1.5 °C in accordance with the Paris agreement. Industrial and civil sectors show a constant decreasing trend in greenhouse gas (GHG) emissions compared to 1990 levels, but this is not the case for the transport sector (European Environment Agency, 2017; Transport & Environment, 2018). Transport accounts for 28.5% of total emissions in the EU and is the only sector which has not seen a decrease since 1990 (Statista, 2020). Although the share of electric passenger vehicles is increasing, emissions emitted by heavy transport such as trucks, maritime shipping and aviation are difficult to remove (Davis et al., 2018). Electrification of transport becomes more difficult as the mass and travel range of the vehicle increases (Gray et al., 2021). For aviation, there are limited options which can be implemented to de-fossilize and there are currently no carbon-neutral commercial plane flights (Timmons & Terwel, 2022; Chiaramonti, 2019). In 2019, the aviation industry was responsible for only 3.4% of total EU emissions, but the number of flights and corresponding emissions are increasing quickly (Statista, 2020; Timmons & Terwel, 2022). Emissions have decreased significantly in 2020 due to COVID-19 pandemic but are expected to double or even triple between 2020 and 2050 as the sector rebounds (Gössling et al., 2021; ICAO, 2020). Therefore, it is urgent to find new solutions and technologies which can help de-fossilize the aviation industry and reduce GHG emissions.

Possible alternatives to fossil-based jet fuel/kerosene are electrical propulsion, hydrogen, biofuels and Power-to-X (P2X) (Faber et al., 2020). These fuels and technologies are in different stages of development, but they are all significantly more expensive to produce compared to conventional fossil jet fuel (Chiaramonti, 2019). The energy density of fossil fuels is substantially higher compared to renewable alternatives, as the former is obtained from concentrated energy deposits underground (Smil, 2015; Capellán-Pérez et al., 2017). Therefore, a substantial amount of land is needed in order to fully de-fossilize the aviation sector by implementing renewable propulsion alternatives. Land requirements for fuel production are important to investigate, as land is becoming a scarcer resource (Lambin & Meyfroidt, 2011) and competition for land is gaining more attention as a subject on regional, national and global levels (Harvey & Pilgrim, 2011). The same is true for electricity, as electrification of demand is gaining more attention in the transport, (residential) buildings and industry sectors (Huismans, 2022). As multiple end uses require more electricity in the future, competition for renewable electricity is expected to increase as a result. Land should be used as efficiently as possible; therefore, it is worthwhile to investigate which alternative fuels for the aviation sector are most efficient in terms of land use.

1.2. Scientific background

Due to the success of electric light duty vehicles during the last decade, the question arises if batteries could help de-fossilize the aviation industry. The main problem with battery-powered planes is the relatively low amount of energy that can be stored. Where hydrocarbon fuel has a heating value of 12,000 W-h/kg, only 250 W-h/kg worth of energy can be stored in batteries (Faber et al., 2020). Moreover, the electric equipment is heavier than equipment used for hydrocarbons. Due to the size and weight of the batteries, battery-powered aviation will be limited to short distances, and therefore will make a small contribution to emission reductions (Langford & Hall, 2020).

Another zero-carbon fuel option is hydrogen, which has an energy density per mass unit that is three times larger than jet fuel. However, the energy density per volume unit is significantly smaller, which means that a larger hydrogen tank is needed to travel the same distance as with a conventional fuel tank (Faber et al., 2020). Additionally, thick insulation walls are required to store the hydrogen, decreasing the amount of possible hydrogen storage and increasing the plane weight. Major plane configuration changes and development of infrastructure are necessary, which is why hydrogen-powered planes are not expected to be available in the near future (Timmons & Terwel, 2022).

With the current aircraft designs and need for high energy density fuels, synthetic hydrocarbons seem like the best option to de-fossilize the aviation sector in the short to medium term as they have similar chemical and physical properties to conventional jet fuel (Adami et al., 2021). Therefore, these so called 'drop-in' fuels can be combusted in existing engines (Faber et al., 2020), but they do require significant amounts of land. Drop-in fuels can be categorized into biofuels and electro-fuels (e-fuels). In the aviation sector specifically, they are referred to as sustainable aviation fuels (SAF) consisting of biomass-based SAF (bio-SAF) and electro-SAF (e-SAF).

Biofuels are fuels which are produced with 1st, 2nd or 3rd generation biomass feedstocks via multiple possible routes (Yilmaz, 2022). Biofuels for aviation are currently the most cost-effective option for sustainable fuels (Davis et al., 2018) and the only alternative which has been produced in commercial amounts (Gray et al., 2021). Fuels produced from 1st generation feedstocks (biomass that is usually edible, such as sugar, starch and vegetable oil) are fully developed and have been commercially available for some time (Bringezu et al., 2007). However, biomass for fuel production (especially 1st generation crops) requires the cultivation of agricultural lands which leads to competition with food security (Davis et al., 2018; Mueller et al., 2011). Between 2% and 3% of global agricultural lands (2% for EU specifically) are used for the production of biofuels, mainly bioethanol and biodiesel (Rulli et al., 2016; European Commission, 2012). An increase in the demand of biofuels can lead to indirect land use change (ILUC) as food producers are displaced and forced to transform natural ecosystems into new agricultural lands (Ahlgren & Di Lucia, 2014; Jering et al., 2013). These original lands can have a high carbon stock (e.g., forests) which will be reduced if the land is converted into agricultural grounds, which could even lead to biofuels producing more emissions compared to conventional fossil fuels (Gawel & Ludwig, 2011). Therefore, the sustainability of biofuel production from 1st generation feedstocks is contested, both ecologically and socio-economically (Bastos Lima, 2021).

Research shows that 2nd generation feedstocks can also be used for biofuel production and can be grown more sustainably (Bhuiya et al., 2016). 2nd generation biofuels are fuels produced from multiple different feedstocks, such as residues from energy crops, lignocellulosic biomass or waste streams (Lee & Lavoie, 2013). The main difference with 1st generation feedstocks is that 2nd generation feedstocks are inedible, so the related biofuel production does not compete directly with food security. Moreover, this type of biomass can be cultivated on marginal lands, which generally require less water and soil fertility compared to arable lands needed for 1st generation biomass (Bhuiya et al., 2016). It should be noted that it is more difficult to convert 2nd generation feedstocks into liquid fuels, as processes become more complex and expensive with increasing complexity in terms of chemical composition of the biomass (Lee & Lavoie, 2013). Therefore, biofuel production from 2nd generation biomass is less developed compared to 1st generation biomass. Finally, 3rd generation feedstocks are currently defined as algae used for fuel production, but these are left out of the scope as production costs are ten times as high compared to conventional oil (Valdovinos-García, 2022). Therefore, the competitivity of algal fuel with other biomass feedstocks is low and is not expected to increase substantially before 2050.

The other pathway to sustainable hydrocarbons is through electro-fuel (or e-fuel) production, also known as the concept of Power-to-Liquid (Schmidt et al., 2018). The main source of carbon for these fuels is CO_2, which can be either captured in concentrated industrial steams (like with carbon capture and storage, or CCS) or with the more novel direct air capture (DAC). E-fuel production is a form of carbon capture and utilization (CCU), which differs from CCS as the obtained CO_2 is used to produce new products, instead of being stored underground. Captured CO_2 can be combined with renewable hydrogen to produce kerosine-like fuels. As these processes, such as DAC, are early in development, costs are high compared to conventional jet fuel production (Faber et al., 2020). Although costs are high, multiple reports claim that e-fuel production requires significantly less land compared to biofuel production and that e-fuel production does not need to take place on agricultural lands (Malins, 2017; Schmidt et al., 2016a; Schmidt et al., 2018; Transport & Environment, 2023). This claim is based on the fact that solar PV converts ± 17 % of solar radiation into useful energy, while only 0.2 % of solar radiation is converted into useful energy by biomass (Searchinger et al., 2017). Therefore, it would be more efficient to produce energy with solar panels compared to using land to cultivate biomass for biofuel production. However, the production of synthetic hydrocarbon fuels such as diesel or SAF, also requires a substantial amount of electricity for DAC and electrolyzers. The reports of Malins (2017) and Schmidt et al. (2016a; 2018) claim that e-fuels produce 5-10 times as much fuel per hectare compared to biofuels, depending on geographical location. However, the claims of these reports are based on simple calculations and multiple assumptions, such as that all produced electricity can be used for e-fuel production without any losses. This is not a realistic assumption, as it is difficult to match the volatile renewable electricity production with the constant electricity demand of fuel production.

In the current body of literature for the comparison between biofuels and e-fuels, a thorough land use comparison is missing. This research aims to fill that gap by extensive modelling of the conversion processes and utilities (such as hydrogen, electricity and heat) required for multiple biofuel and e-fuel production routes, specifically for SAF. This research combines relevant data of the most recent studies on bio-SAF and e-SAF conversion processes and aims to create a range of data to increase robustness of the land use comparison. Additionally, conversion processes of bio-SAF and e-SAF production are combined to increase overall land use efficiency. For instance, CCU is implemented in bio-SAF processes where CO_2 is emitted and wind power is combined with biomass cultivation. It is worthwhile to research these combinations, as the impact of these combinations on land use has not been studied as of yet.

1.3. Problem definition & research questions

The production of SAF for the EU aviation industry is limited to land in the EU in this research, SAF is not imported from other regions in the world. There is typically more land available outside of Europe, but production in the EU is preferred as production close to demand minimizes the required infrastructure and transport, while also increasing energy security. EU countries have always been dependent on other nations for their fossil fuel supply, 96% of crude oil has been imported from other countries in 2020 for example (Siemens Gamesa, 2022). As the economy of the EU is dependent on the supply of stable and affordable energy, it is important to have control on as much energy supply as possible, especially in light of the impacts of the conflict between Ukraine and Russia (European Commission, 2022; Porsborg-Smith et al., 2022).

There are multiple routes to convert biogenic feedstocks into SAF, such as (waste) oils, dedicated energy crops and woody biomass (Neuling & Kaltschmitt, 2015). Routes are only considered if they are approved by ASTM international, which is a safety approval required for use in commercial flights (ICAO, 2021). There are currently four ASTM approved bio-SAF processes, which use either food/waste oil, woody biomass, sugar-, starch- and lignocellulosic crops (Neuling & Kaltschmitt, 2015).

Two e-SAF routes are considered, which are further elaborated upon in the next section of this research. A combination of solar and wind energy is used for the electricity production, as their power profiles complement each other which creates a more constant power output during the day and year (Monforti et al., 2014). Only onshore wind will be included, as offshore wind does not have an impact on land-use. The required CO_2 will be collected only with DAC. Concentrated industrial CO_2 streams are initially not considered in the e-SAF routes, as synthetic hydrocarbons produced out of CO_2 from fossil sources cannot be regarded as 'sustainable' aviation fuel (Bracker & Timpe, 2017). By reusing the captured CO_2 from fossil sources for fuel production, it contributes to climate change when SAF is combusted in air plane engines. As some biofuel conversion routes do emit CO_2, concentrated biogenic CO_2 streams will be included in the analysis to maximize carbon-efficiency. In this case, the carbon in CO_2 which would otherwise be emitted, is upgraded to SAF through e-SAF conversion processes. Electric propulsion and hydrogen fuel are not considered due to their early stage of development and small expected contribution to GHG emission reductions in the aviation sector. Moreover, bio-SAF and e-SAF have similar properties to conventional jet fuel and therefore fit in easily into existing infrastructure and plane design. The following main research question is formulated:

What is the optimal bio-SAF or e-SAF production route for de-fossilizing the aviation industry in the EU in terms of land use efficiency?

To answer the main research question, multiple sub questions can be formulated. First, the potential of (1^{st} & 2^{nd} generation) biomass, solar and wind energy within the EU is discussed. As these potentials can vary substantially across the EU, two regions within the EU are selected as case studies. The availability of land also plays a role in the choice of region for the case studies, which is discussed along with prior research on marginal and surplus land in the EU.

Next, the necessary conversion processes within the bio-SAF and e-SAF production routes are identified. The conversion efficiencies and utility requirements, such as hydrogen, electricity and heat, are the most important parameters for determining the land use of the production routes. This data is collected by consulting literature on bio-SAF and e-SAF production. The land use of the SAF production routes is determined by building a conversion model in Excel. Land use breakdowns are created for both case studies, to indicate the most important contributors to the land use and electricity requirement of the bio-SAF and e-SAF production routes. As optimizing the land use of fuel production is of great importance, combinations of bio-SAF and e-SAF production routes are examined too.

1. Which regions in the EU have the highest biomass, solar and wind energy potentials and available area for SAF production?
2. What are the necessary conversion processes and utilities for the bio-SAF and e-SAF production routes?
3. What is the land use of the bio-SAF and e-SAF production routes in the proposed regions?
4. What are the most important contributors to total land use and electricity requirement of the bio-SAF and e-SAF production routes?

2. Theory

2.1. Land use competition and efficiency

Land use can be defined as "the human use of land, representing economic and cultural activities such as agricultural and residential uses" (Environmental Protection Agency, 2022). Land competition between multiple land uses is expected to increase the next decades, mostly due to changes in food and energy supply. More than half of global habitable land is used for agriculture, of which 77% is for livestock (and feed production for the livestock) and the remaining 23% is for crop cultivation (Statista, 2019). Almost all cropland is used for the production of food and the amount of land needed is expected to increase due to the growing population (Harvey & Pilgrim, 2011). On the other hand, petrochemical resources are slowly being phased out but the total demand of energy is increasing. Therefore, alternatives such as bioenergy and solar energy are deployed more, thus leading to higher land use. The increase in food and energy demand puts more pressure on global land use and leads to higher LUC and ILUC (and therefore GHG emissions) (Harvey & Pilgrim, 2011). The trade-off between these three factors is known as the food, energy and environment trilemma and is schematically displayed in Figure 1 (Tilman et al., 2009).

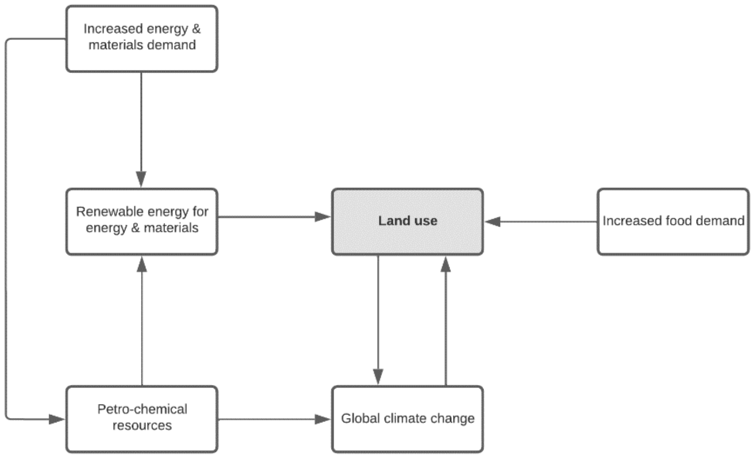

Figure 1 - Food, energy and environment trilemma including pressuring factors (adapted from Harvey & Pilgrim, 2011)

Where fossil-based jet fuel can be produced with a relatively small amount of land, SAF is produced with biomass or renewable energy which generally require large amounts of land. In this research, land use refers to all land that is used for SAF production, consisting of the land required to produce carbon feedstocks (biomass or CO_2) and utilities such as electricity or hydrogen. Additionally, land is only 'used' when the primary activity withholds other activities from taking place. This is the case with crop cultivation for biofuels or solar farms for large scale electricity production, as no other activity can take place on the land that is used for these activities. One exception is agri-solar photovoltaics, which enables dual land use by combining agriculture with solar PV. Agri-solar photovoltaics are not included in this research as they prevent sunlight from reaching crops. Another exception is wind energy; large distances are required between turbines to ensure the maximum efficiency, but other activities can take place on the ground in between the turbines, such as biomass cultivation for biofuels or solar PV to produce additional electricity.

The quality of land is also important to take into account when assessing land use. There is a distinction between fertile arable lands and less fertile marginal, unused and abandoned lands. The former is more valuable and experiences more competition for land, as it can be used to produce both food and energy from 1st generation biomass. The latter type of land is characterized by adverse biophysical conditions, consisting of 1) harsh/extreme climate, 2) soil too wet, 3) low fertility soil, 4) soil contamination, 5) unfavorable root conditions and 6) unfavorable site conditions as shown by Elbersen et al. (2018). These conditions make it difficult to grow 1st generation crops on marginal lands, but 2nd generation energy crops can produce high yields in less favorable conditions (Lewandowski, 2015; Lewandowski et al., 2016). Therefore, bio-SAF can either be produced from 1st generation crops grown on arable lands or from 2nd generation energy crops grown on marginal lands.

E-SAF production is less dependent on the quality of land, compared to bio-SAF production. The carbon feedstock of e-SAF, CO_2, is obtained directly from the atmosphere with DAC. E-SAF production requires large amounts for electricity for the capture of CO_2 and hydrogen production, but the performance of wind and solar PV is not dependent on soil quality. Solar and wind energy can be produced on both arable and marginal lands. However, renewable electricity production (especially solar PV) on degraded and marginal lands is preferred due to the increasing scarcity of fertile land. Some studies even argue that solar PV provides benefits for the environment and vegetation in areas with degraded lands (Hernandez et al., 2014; Hernandez et al., 2015; Vervloesem et al., 2022). A study by Li et al. (2018b) has shown that large scale wind and solar energy production can increase the temperature and the amount of precipitation in degraded areas, leading to more vegetation. This creates a positive feedback loop, as vegetation leads to additional precipitation. This shows that renewable electricity production could potentially be used to slowly return degraded and marginal lands to their initial states.

Independently of the land used for SAF production, it is important to use the available land as efficiently as possible. Land use efficiency typically refers to the amount of societal benefits reaped from land use activities, generally the amount of output of a unit of land like yield or economic benefit (Auziņš et al., 2013). In this research, land use efficiency indicates the amount of land required to produce a unit of SAF. The land use efficiency of SAF production is dependent on geographical factors such as biomass cultivation-, solar energy- and wind energy potentials.

2.2. Biomass cultivation-, solar energy- and wind energy potentials in the EU

Within the EU, agriculture is the primary source of land use, accounting for approximately 39% of all land. The agricultural lands consist of arable lands, permanent crops (such as fruit and olive trees), pastures and grasslands. Forestry accounts for 36% and unused or abandoned areas take up 15% of the land in the EU. The latter can also be characterized as marginal lands. The remaining 10% is used for residential uses, industry and fishing (European Commission, 2021).

As mentioned in the introduction, only a small percentage of agricultural land is used for biofuel production, meaning that the vast majority is used for food and feed production. However, a substantial amount of land is needed in the future to produce biomass and renewable electricity for the production of renewable fuels. It is of utter importance that renewable fuel production does not compete with food production in terms of land and valuable natural lands and carbon stocks (such as forests) should be kept intact to reduce the environmental impacts of fuel production. This ensures that (future) food supply is not compromised by fuel production and reduces the risk of (I)LUC. This begs the questions on which lands and in which regions within the EU biofuel or e-fuel production should take place.

Ideally, renewable fuel production takes place on so called surplus land. Surplus land is an umbrella term for all land that is potentially available for renewable fuel production, specifically biofuels (Dauber et al., 2012). Surplus land consists of 1) lands which are unfit for the production of food, feed or other renewable sources due to lacking biophysical conditions (such as marginal and abandoned lands) and 2) arable lands which become available for fuel production due to the already satisfied food and feed demand (Krasuska et al., 2010; Brinkman et al., 2018). The prior type of surplus land (mostly marginal) can be used for the cultivation of 2nd generation biomass or renewable electricity production. Some of these lands do need to be excluded due to prohibitions of socio-economic activities on protected lands or to remoteness of the lands, making socio-economic activities less attractive (European Commission, 2021). The second type of surplus land can arise due to increasing crop yields for food and feed production and due to decreasing population in some EU countries. These lands are more valuable due to better biophysical conditions and could be used for 1st generation biomass cultivation.

Unfortunately, there is no recent research on the quantification and locations of surplus lands in the EU. Krasuska et al. (2010) have researched the increase of surplus land in the EU with scenarios for 2020 and 2030, by assessment of expected increasing agricultural efficiencies and population changes. The results are shown in Appendix 1, Figure 19. Krasuska et al. (2010) found that surplus land is expected to arise most in Eastern Europe, especially Poland, Hungary Romania and Bulgaria. These countries show high potential for land availability for fuel production due to high expected crop yield increase, decrease in population and high food self-sufficiency. Spain and Greece also have high shares of surplus land, due to the high amounts of fellow and marginal land in the countries. These shares do not increase substantially over the years, so this surplus land is expected to be of lesser quality compared to lands in Eastern Europe for example. This is also reinforced by the earlier mentioned research by Elbersen et al. (2018) and Allen et al. (2014), their results are shown in Figure 2 and Appendix 1, Figure 20 respectively. Well-developed countries in North-Western Europe have a substantial amount of land without natural constraints, but populations are expected to increase in these countries, leading to higher land requirements to satisfy local food demand.

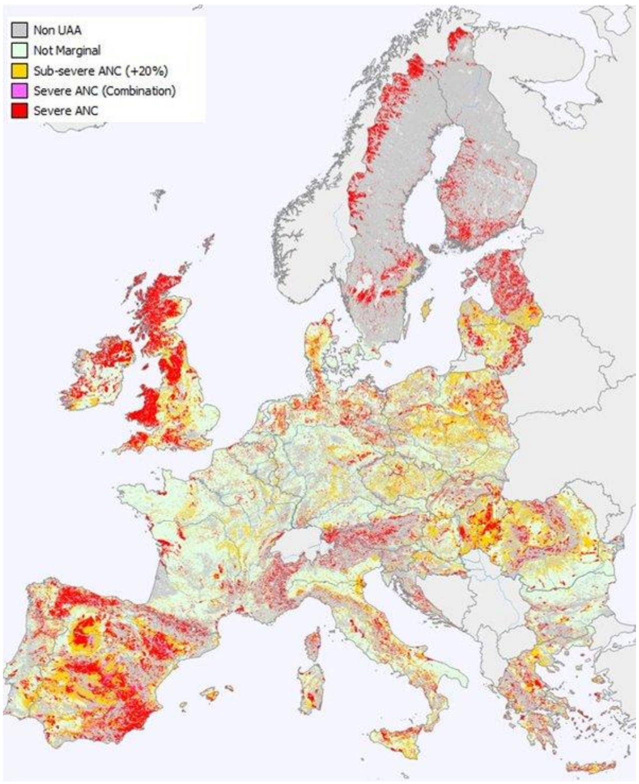

Figure 2 - Marginal land, or Areas with Natural Constraints (ANC), in the EU. UAA stands for Utilized Agricultural Area. (Elbersen et al., 2018)

Aside from the type of land on which biomass is cultivated, the potential of renewable fuels (specifically biofuels) is dependent on the type of crop and its yield per area unit. There are no recent studies on the potential of 1st generation biofuels in the EU, but food crops generally have the highest potential in areas without natural constraints as shown in Figure 2. 1st generation crops such as maize, rapeseed and sugar beet are most often selected for biofuel production due to their high yields and relatively simple conversions into fuels. Countries in (South) Western Europe generally provide the highest yields for these crops, but they can vary over the years substantially due to their dependency on weather conditions (Ritchie et al., 2022).

Regarding 2nd generation crops, Vera et al. (2021) performed a study on the biomass potential of 2nd generation crops by only assessing marginal lands which meet the 2030 sustainability criteria of the Renewable Energy Directive II (REDII), see Figure 3. The results of this study are in line with the marginal lands identified by Elbersen et al. (2018), showing most lands fit for production in Spain, Greece, parts of the UK, Scandinavia, the Baltics and central Italy. The right side of Figure 3 shows the type of lignocellulosic crop best fitted for each region, on which the biofuel potentials are based on. Miscanthus and switchgrass are the crop of choice in many regions in the EU, due to their adaptability to different climates. Giant reed is the best choice in warmer climates, the crop delivers on average the largest yields of all crops and has the highest water-use efficiency. Reed canary grass is characterized as the crop with the lowest theoretical yield, but highest tolerance and is therefore cultivated in areas where the temperature is too low or there is too much precipitation for the other crops. Eucalyptus is also tolerant to drier climates like giant reed and reed canary grass, but has an average lower yield compared to giant reed. Although willow and poplar are grown in almost each region in the EU and cardoon is grown in the mediterranean, they do not appear in Figure 3 due to their relatively low yields for biofuels.

Although areas such as Northern Spain, the UK, the Alps and Scandinavia contain areas fit for 2nd generation biofuel production, they have low potentials according to Vera et al. (2021). The Iberian peninsula (in specific Southern Spain), Greece, Hungary and Italy show the highest potential for biofuel production, due to the large amounts of marginal land fit for production with giant reed and miscanthus, which both have high yields.

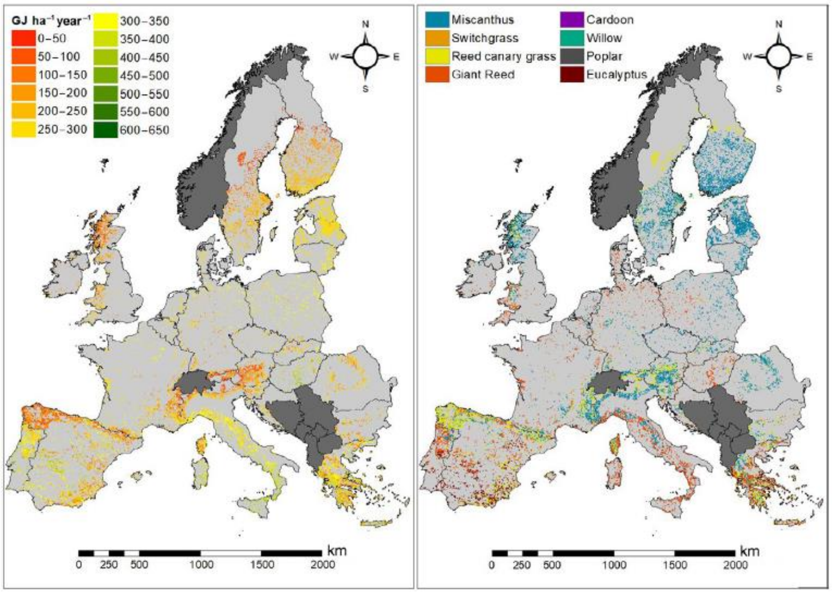

Figure 3 - Maximum yield potential of biofuels produced from lignocellulosic (2nd generation) crops in the EU (Vera et al., 2021)

Solar and wind energy

Similar to biofuels, the potential of e-fuel production is also dependent on location. The main variable affected by the location is the electricity generation, which is done with solar PV and wind turbines. Electricity generation is substantially less dependent on the type of land compared to biomass; PV panels and wind turbines do not produce less electricity when placed on marginal or inarable lands, compared to (surplus) arable lands. Marginal lands are often located in remote areas (see Figure 2), so the installment of large scale solar PV or wind farms for electricity generation would either require the e-fuel plant to be close to electricity generation or require a more complicated electricity transport system, as electricity generation would be located further away from the plant where it is used. Both options have disadvantages, the first option having high costs for maintenance as the plant would be difficult to reach and the second option having high costs for additional transport cables and batteries to ensure a secure electricity supply. In both cases, the construction, operation and maintenance of solar PV and/or wind farms in remote areas are difficult and costly, complicating the feasibility of the project (Hernandez et al., 2015).

The potential of solar PV production is dependent on the solar irradiation. A map of the yearly solar irradiation in Europe is shown in Figure 4. The Southern countries within the EU (Spain, France, Italy & Greece) have the highest yearly irradiation as they are closest to the equator. The Balkan countries also show good potential. The map also shows that there are large differences between countries, as parts of Spain have solar irradiations twice as high as the irradiation of countries located in North and Central Europe. The eventual solar PV potential is also influenced by the type of panel used (and its conversion efficiency) and the time of year, as the sun is more powerful during summer and the sun shines for more hours during the day.

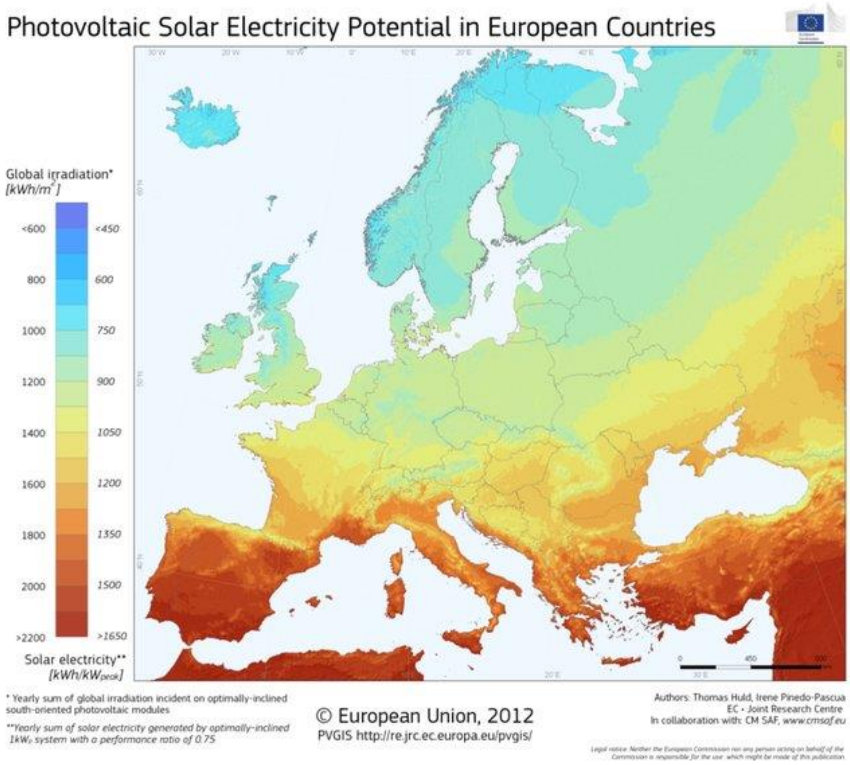

Figure 4 - Global irradiation map of Europe (JRC, 2014)

The potential of wind energy is dependent on wind speed, which varies substantially across regions within Europe (see Figure 5). Figure 5 shows that wind speeds are generally highest at coastal areas in Northern Europe, with exceptions in Northern Spain, Southern France and the Greek isles. Wind speeds and thus wind potentials are lower in the Southern parts of Europe, opposed to solar irradiation and PV potential. Especially the UK and countries around the North and Baltic sea show high wind energy potentials. Areas such as Northeastern Spain, Northwestern France and other regions in Northeastern Europe also experience significant wind speeds above 5 m/s annually, which are still twice as high as wind speeds in Southern Spain, areas south of the Alps or large parts of the Balkans. This difference in wind speed is important to take into account as the wind power potential theoretically increases by a factor of 8 when the wind speed is doubled (IRENA, n.d.). Aside from wind speed, the power potential of wind energy is also influenced by the size of the turbine and the length of the blades. New turbines (generally with a capacity larger than 3 MW) are substantially larger and have larger swept areas compared to older models. The hub height of the turbine has a large impact on the turbine potential, as wind speeds increase at higher altitudes. There are many variables deciding the electricity generation potential of a wind turbine, which makes it hard to compare one wind farm with another.

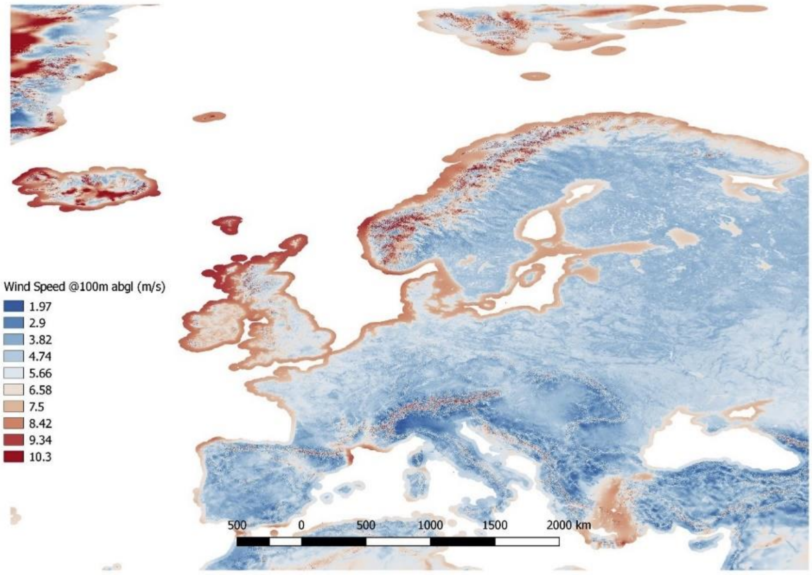

Figure 5 - Annual mean wind speeds in Europe at 100m above ground (Enevoldsen et al., 2019)

2.3. Bio-SAF and e-SAF production routes

2.3.1. Bio-SAF production routes

Only ASTM approved SAF conversion routes are examined in this research, an overview is shown in Figure 6. The four approved routes are hydro processed esters and fatty acids (HEFA), direct sugar to hydrocarbon (DSHC), alcohol to jet (AtJ) and biomass to liquid (BtL). Where HEFA uses waste and food oils as feedstock, DSHC and AtJ are used for sugar and starch crops and BtL mainly uses lignocellulosic crops as input. Although DSHC is ASTM approved, the conversion route is the most expensive of all alternative SAF production routes due to the complexity of the process and low efficiency (Bauen et al., 2020). Moreover, the DSHC process only produces a large hydrocarbon called 'Farnesane' which can currently only be blended with conventional jet fuel to a maximum of 10% (Neuling & Kaltschmitt, 2015; E4tech, 2021). As AtJ is also used to convert sugar and starch crops into SAF, this research will focus on this technology instead of DSHC. Therefore, the investigated bio-SAF routes are HEFA, AtJ and BtL. Their process diagrams are shown in Figure 7 and the main processes can be found in formulas, see Appendix 2.

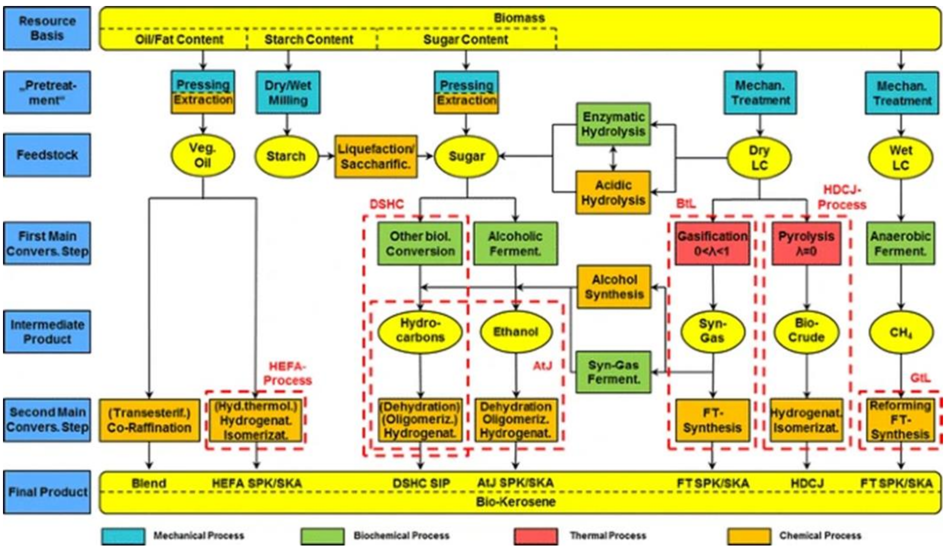

Figure 6 - Overview of conversion processes from biomass feedstock to bio-SAF (Neuling & Kaltschmitt, 2015)

Hydro processed esters and fatty acids/HEFA

The HEFA route requires oils as input, which can be extracted from feedstocks such as rapeseed, sunflowers, soybeans and palm. Rapeseed is used as feedstock for the HEFA route, due to the relatively high vegetable oil yield per hectare, especially compared to sunflower and soybean oil (Jazayeri, 2015; Triangle Biofuels Industries, Inc., n.d.). It is also an abundant feedstock in the EU, as the EU is the largest producer of rapeseed oil worldwide (Gaber et al., 2018; Statista, 2023b). Palm and jatropha oil have higher yields per hectare but are not considered, as they require tropical regions and cannot be cultivated in Europe.

During rapeseed harvest, rape straw is collected as byproduct. The straw is not fed into the HEFA process as it does not contain oil, but it can be used for other purposes. Rape straw is combusted for heat production in a research by Gupta et al. (2022), but another method is to plough the straw back into the soil to enhance the organic content and increase future yields (Fridrihsone et al., 2020). The latter is assumed in this thesis, as rapeseed yields are relatively low compared to other biomass feedstocks. Pre-treatment of the oil crop is the next step, which entails drying of the feedstock, oil extraction and pre-refining the oil. The biomass is dried to reduce moisture content which requires a substantial amount of heat. Oil extraction generally consists of cold pressing (mechanical pressing at low temperature) and further extraction with a solvent, such as hexane. Concentrated rape meal is produced as byproduct, which is high in protein and is generally used as animal feed. The obtained oil is pre-refined to remove impurities such as excess water, solvent and phospholipids (Gupta et al., 2022). Pure vegetable oil is obtained after pre-treatment.

Within the HEFA process, vegetable oil is hydrotreated, hydrocracked and isomerized into a range of fuels. The fuel mixture is distilled similar to conventional oil to end up with jet fuel. Vegetable oil consists mostly of triglycerides, but also contains diglycerides, monoglycerides and free fatty acids (FFA). During hydro-treatment, the glycerides and FFA's are converted into alkanes in a few steps, see Appendix 2.

The most important steps are the propane removal, which separates the three-branched molecules into long, single chain molecules, and the removal of oxygen. The obtained mix of alkanes (also called linear paraffins) needs to be isomerized and hydrocracked as final step, requiring hydrogen and catalysts. Isomerization turns the long chain hydrocarbons (linear paraffins) into branched hydrocarbons (iso-paraffins) to reduce the freeze point, necessary to meet jet fuel A1 standards. Hydrocracking is applied to split the long chain paraffins into smaller chain paraffins, creating jet fuel similar to kerosine. Aside from jet fuel, the obtained fuel mix generally also contains diesel and naphtha. As these are useful co-products, they also need to be accounted for when assessing total land use. HEFA is a commercial process, so the TRL is 9 (Sotelo-Boyás et al., 2012; Starck et al., 2016; Tao et al., 2017; Goh et al., 2020; Monteiro et al., 2022).

Alcohol to jet/AtJ

Within the AtJ route, sugar is converted into ethanol and butanol with alcoholic fermentation, generally from sugar or starch crops (although lignocellulosic feedstocks can also be used, see Figure 6). As it is common practice to produce ethanol from corn, corn grain is used as feedstock for the AtJ production route. When corn is harvested, the corn grain is split from the corn stover, which is a useful byproduct. Corn stover has a relatively high energy content and can be combusted for heat production or gasified to convert into other useful products, for example. Sugar extraction from starch crops is more complex compared to sugar crops, as the sugar is not readily available for fermentation. First, the corn grain is pre-treated by dry-milling. After milling, the corn starches are cooked and liquefied by the enzyme α-amylase and are converted into liquid sugars by gluco-amylase afterwards (Kaltschmitt & Streicher, 2009). The sugar is extracted by washing the sugar out of the corn grain with the counter-current process (Pechstein et al., 2018). A main byproduct of this process are dried distillers grains and solubles (DDGS). Similar to rape meal, this byproduct is high in protein and can be utilized as a substitute for conventional animal feed.

Next, the acquired sugars (consisting mostly of glucose) are converted into alcohols through fermentation, such as ethanol and butanol. Ethanol fermentation is a mature process and has been carried out for centuries, butanol fermentation is relatively new and still in the R&D phase (Pechstein et al., 2018). Therefore, this research focuses on ethanol as main alcohol to convert into jet fuel. The main drawback of ethanol production is the associated released CO_2. However, the produced CO_2 is almost pure (> 99 vol %) and can be easily captured and stored or utilized for other processes (Huang et al., 2020).

The ethanol is dehydrated and converted into ethylene, which is converted further into long chain alkenes with oligomerization. Alkenes/olefins are unsaturated hydrocarbons and cannot be used directly as jet fuel, due to their instability. The alkene mixture is hydrogenated to convert them into alkenes, with the use of catalyst at ambient temperature and pressure. Finally, the alkane mixture is distilled and fractionated to end up with usable jet fuel. The mixture also contains diesel and gasoline as useful co-products (Geleynse et al., 2018). The TRL of the AtJ route is 6-7 for sugar/starch feedstocks and slightly lower for lignocellulosic feedstocks (Bauen et al., 2020; Neuling & Kaltschmitt, 2015; Wang & Tao, 2016; Tiwari et al., 2023).

Biomass to liquid/BtL

The BtL route converts biomass (generally 2nd generation crops, such as dedicated energy crops or residues) into syngas by gasification. The syngas can be upgraded further into liquid fuels such as jet fuel with FTS. Switchgrass is used as feedstock for the BtL production route, as it is a versatile perennial grass which can be grown in areas with varying conditions, illustrated by Vera et al. (2021). Miscanthus or woody crops, such as willow or eucalyptus, can also be used but the chemical compositions and syngas yields are similar to those of switchgrass. The first step is pre-treatment of switchgrass, which is necessary to decrease particle size of the feedstock. This increases the surface area of the feedstock, making the heat transfer and biomass conversion during gasification more efficient. Biomass can be chopped and grinded during pre-treatment, but drying the biomass is most important. By reducing the moisture content, the gasification efficiency is improved and hydrogen is removed from the biomass which is unfavorable in fuel synthesis later in the process (Hu et al., 2012).

Two types of gasifiers can be used, a 'low' temperature fluidized bed gasifier (800 – 900 °C) and a high temperature entrained flow gasifier (1300 °C). Fluidized bed gasifiers are less capital intensive compared to entrained flow gasifiers, but the latter have higher carbon efficiencies (You & Wang, 2011). The entrained flow gasifier is preferred due to its higher efficiency, but it requires the feedstock to have a uniform and small particle size which serves a problem for biomass due to its fibrous characteristics (Damartzis & Zabaniotou, 2011). Fluidized bed gasifiers are more flexible when it comes to feedstocks and are used most often for gasification of 2nd generation biomass, especially dedicated energy crops such as switchgrass and miscanthus (Ciliberti et al., 2020).

The biomass enters the gasifier where it is pressurized and gasified with a mixture of pure oxygen and steam. The oxygen is obtained by feeding ambient air through an air separation unit, which splits the oxygen from the air mixture by using electricity. Steam is generated by heating water in a boiler, powered by produced syngas or additional biomass. During gasification, a mixture of CO, CO_2, H_2O, H_2, CH_4 and other CH molecules is formed by thermo-chemically breaking down (hemi)cellulose and lignin structures within the biomass, see Appendix 2.

Next, the obtained syngas is cleaned and the H_2 to CO ratio is adjusted to the optimal FT ratio with the water gas shift (WGS) reaction (You & Wang, 2011). The readjusted mixture of H_2 and CO is fed into the Fischer-Tropsch (FT) reactor, where they are combined to form a wide range of hydrocarbons, such as alkenes/olefins, alkanes/paraffins and other compounds like alcohols and aromatics (Wang & Tao, 2016). The initial share of jet fuel range hydrocarbons can be increased by hydro-treatment, such as hydrogenation and hydro-cracking. During hydro-treatment, hydrogen reacts with longer hydrocarbons to split them into shorter chain alkanes. As final step, the mixture is distilled to end up with a mixture which fits the desired jet fuel output profile. Fischer-Tropsch synthesis (FTS) generally yields between 65% and 85% diesel and jet fuel products (Fasihi, 2015). The remaining useful output consists of naphtha (and in some occasions LPG). Jet fuel can account for a maximum of 50% of total output according to Albrecht et al. (2013), although other research claims to achieve higher yields (Li et al., 2018a). The TRL for biomass feedstocks is 7-8, while FT synthesis from coal and gas is commercially available (Bauen et al., 2020; Neuling & Kaltschmitt, 2015; Wang & Tao, 2016; Tiwari et al., 2023).

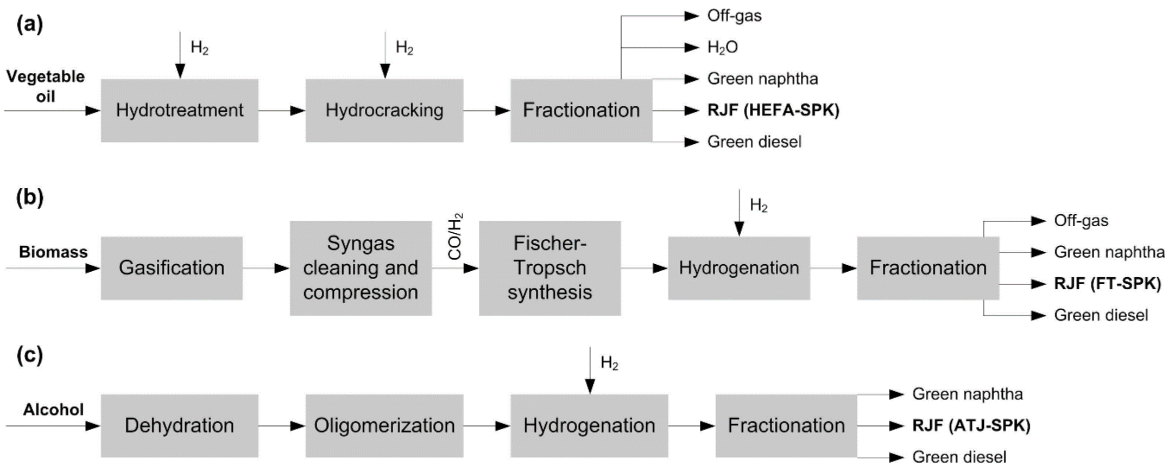

Figure 7 - Biomass conversion pathways, namely HEFA, BtL/FTS and AtJ (Klein et al., 2018)

2.3.2. E-SAF production routes

E-SAF production is defined as collecting CO_2 from ambient air, producing hydrogen from renewable electricity through electrolysis and upgrading the CO_2 to hydrocarbons such as SAF. SAF production through the e-fuel route consists of DAC, an electrolyzer for hydrogen production, the plant required for the conversion into fuel and renewable electricity to power all processes. The conversion of CO_2 and hydrogen into SAF can take place via methanol production and upgrading, or via FTS (Sharma et al., 2021).

DAC
Direct air capture is the process of capturing CO_2 from ambient air. Two types of DAC are the furthest in development: low temperature (LT) DAC, which uses solid adsorbents and operates under low pressure and medium temperature (80 – 120 °C) and high temperature (HT) DAC which uses liquid adsorbents and operates under high temperature (300 – 900 °C) (IEA, 2022a). LT DAC is expected to be more scalable in the future, as it requires significantly less heat compared to HT DAC and is the least expensive technology of the two (Fasihi et al., 2019; McQueen et al., 2021). Moreover, waste heat from fuel conversion processes can be used as heat input for LT DAC, decreasing heat demand from external sources and associated costs (Fasihi et al., 2017; Ram et al., 2018). Where HT DAC requires significant amounts of water per unit of captured CO_2, LT DAC actually produces water as a byproduct from moisture from the atmosphere, which can be turned into hydrogen (Fasihi et al., 2017). Because of these benefits of LT DAC over HT DAC, the latter is not considered in this thesis.

LT DAC consists of two consecutive processes which occur in the same unit, adsorption and desorption (or regeneration). The two processes are shown in Figure 8. In the adsorption process, ambient air enters the DAC chamber naturally or with the use of fans. The CO_2 chemically binds with the solid sorbent, typically an amine or carbonate, while the remaining air without CO_2 leaves the chamber. When the sorbent is fully saturated with CO_2, the chamber closes and the second process begins.

In the desorption process, the fans are turned off and the inlet of the DAC unit is closed. The CO_2 is released from the sorbent by increasing the temperature and decreasing the pressure inside the chamber, the exact conditions are dependent on the type of sorbent. The CO_2 is purified by removing any impurities and a pure stream of CO_2 leaves the DAC chamber (Fasihi et al., 2019). Some DAC systems also produce water as a byproduct, this is also dependent on the type of solvent.

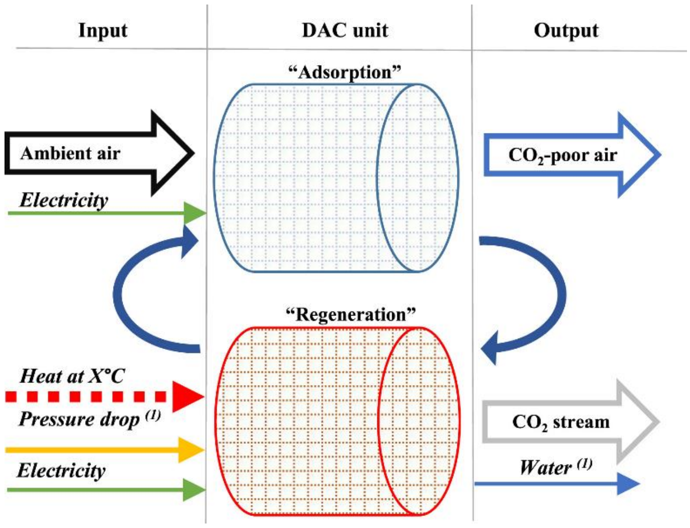

Figure 8 – Schematic visualization of LT DAC operation (Fasihi et al., 2019)

Hydrogen production with electrolyzer
Polymer electrolyte membrane (PEM) electrolyzers are the most developed type of electrolyzer and are commercially available (Bertuccioli et al., 2014). Moreover, PEM electrolyzers are expected to have substantially lower costs and higher efficiencies in the near future, compared to other electrolyzer types such as alkaline (IEA, 2015; Noack et al., 2015). The PEM electrolyzer produces gaseous hydrogen from liquid water, with oxygen as byproduct. Hydrogen ions and oxygen are produced in the electrolyzer anode by splitting water, which also results in two separate electrons. In the cathode, the electrons are bound to the hydrogen ions to form hydrogen, see Figure 9. PEM electrolysis requires a substantial amount of electricity as input, which is provided by renewable sources such as solar PV and wind turbines. PEM electrolysis generally operates at a temperature of 80 °C (IEA, 2015), this temperature can be reached by using heat from other processes.

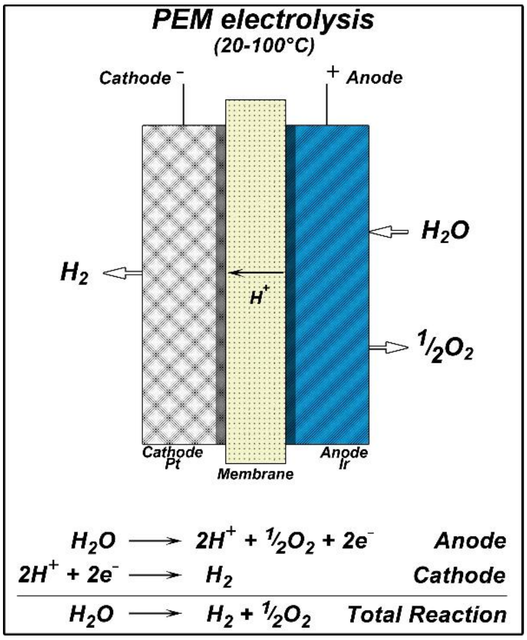

Figure 9 - Schematic visualization of PEM electrolyzer

Conversion of CO_2 and hydrogen (Methanol upgrading)
The first route to produce SAF from CO_2 and hydrogen is through methanol production. Methanol synthesis takes place through hydrogenation of CO_2, generally with a copper catalyst (Borisut & Nuchitprasittichai, 2019; Malins, 2017). Next, methanol is converted into dimethyl ether (DME) and is further upgraded to long-chain hydrocarbons through oligomerization, similar to how ethanol and butanol are converted in the AtJ route (Ruokonen et al., 2021). ExxonMobil is the first to apply this series of reactions in their methanol

to gasoline (MTG) in the 1970's. They further developed the process into the methanol to olefins (MTO) and Mobil's olefins to gasoline and distillate (MOGD) processes in the 1990's. By combining these processes, methanol can be converted into gasoline, diesel and jet fuel (Avidan, 1988), see equations (1) until (5). A substantial amount of water is also produced, due to the large amount of dehydration reactions in the process. The last step is to hydrotreat the olefins to create paraffins (alkanes) and distilling the mixture to end up with SAF (Malins, 2017; Schmidt et al., 2016b; Schmidt et al., 2018; Terwel & Kerkhoven, 2018).

$$3H2 \; + CO2 \; \leftrightharpoons CH3OH + H2O \tag{1}$$

$$2CH_3OH \rightarrow CH_3 - O - CH_3 + H_2O \tag{2}$$

$$CH_3 - O - CH_3 \rightarrow (CH_2)_2 + 2H_2O \tag{3}$$

$$\frac{n}{2}(CH_2)_2 \rightarrow C_nH_{2n} \tag{4}$$

$$C_nH_{2n} + H_2 \rightarrow C_nH_{2n+2} \tag{5}$$

Methanol upgrading typically yields 81% (mass) mid-distillates, containing jet fuel and diesel (Schmidt et al., 2016b; Malins, 2017). The remaining part of the fuel mixture consists of diesel, gasoline, LPG and occasionally fuel gas (Liebner et al., 2004; Ruokonen et al., 2021). It is important to note that this route is not ASTM approved as of now (Drünert et al., 2020; E4tech, 2021). However, this route is considered as renewable methanol is expected to be an important feedstock for the chemical and transport sector (IRENA, 2021). Therefore, conversions of methanol into other end-products are likely to attract more attention in the near future, including SAF. Moreover, all individual processes shown above are commercially proven, only the combination of processes has not reached commerciality. The full conversion of CO_2 and hydrogen into SAF through methanol production is shown in Figure 10.

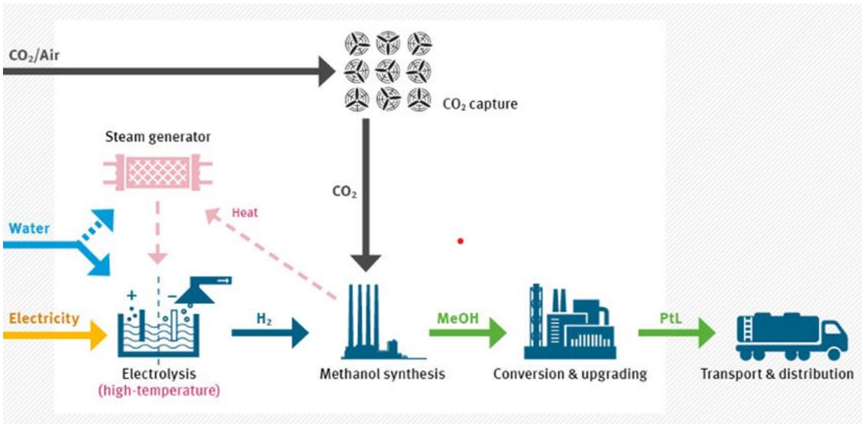

Figure 10 - Production route of e-fuels through methanol synthesis (German Environment Agency, 2016)

Conversion of CO_2 and hydrogen (Fischer-Tropsch synthesis)
The second SAF production route is through FTS, similar to the BtL route. The main difference between the two is that the BtL route uses syngas (combination of hydrogen and CO) as input and the e-fuel route starts with a mixture of hydrogen and CO_2. The CO_2 is first converted into CO with the reverse water gas shift (RWGS) reaction, see equation (6). The RWGS operates at high temperatures between 800 and 1000 °C, at a pressure of 30 bar. The inverse of the RWGS, the water gas shift (WGS), is commercially available for the hydrogen production from natural gas. The RWGS is used less often and has a TRL of 7 (Concawe, 2022).

$$CO2 \; + \; H2 \leftrightharpoons CO + H2O \tag{6}$$

The obtained CO is fed into the FT reactor with additional hydrogen, where the CO is hydrogenated into long hydrocarbons (Schmidt et al., 2018). This step is similar to the FT reaction in the BtL route and is therefore ASTM approved with a TRL of 9 (Malins, 2017). A mixture of hydrocarbons is obtained, consisting of paraffins, olefins, alcohols and aromatics. The hydrocarbon mix is hydrocracked to convert olefins into paraffins and to decrease the chain length of long-chain paraffins. Finally, the mixture is distilled and refined to fit the desired jet fuel output profile. Low temperature (190 – 250 °C) FTS generally yields between 65% and 85% mid-distillates, containing mostly diesel and jet fuel products (Fasihi, 2015; Concawe, 2022). LPG and naphtha can also often be found in the fuel mixture. Jet fuel can account for a maximum of 50% of total output according to Albrecht et al. (2013). The full conversion of CO_2 and hydrogen into FT fuels is shown in Figure 11.

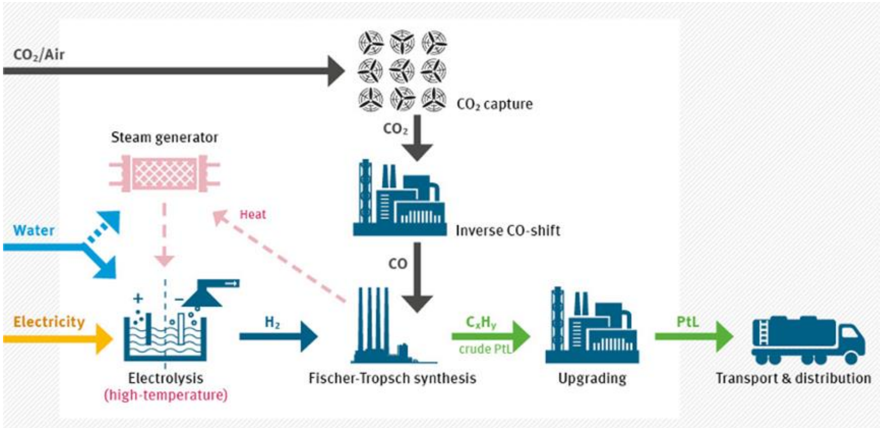

Figure 11 - Production route of e-fuels through FTS (German Environment Agency, 2016)

3. Methods

3.1. Conversion model

The previous section has shown that the potential of biomass, solar and wind energy is dependent on geographical location. Therefore, two case studies are carried out to assess the influence of geographical location on the land use of SAF production routes. The first case study is carried out in Spain, where biomass potential and solar irradiation are relatively high. The second is done in Poland, which has a lower biomass potential and solar irradiation compared to Spain, but a higher average wind energy potential. These two countries are chosen as they both have large amounts of available area for biomass cultivation and electricity production, but they have large differences in climate and soil quality. It is important to note that within countries, there are still large differences in biomass and renewable electricity potential on a local level.

The main research question is answered by designing a conversion model in Excel for three bio-SAF production routes (HEFA, AtJ & BtL) and two e-SAF production routes (methanol upgrading/e-MeOH & Fischer-Tropsch synthesis/e-FT), see **Error! Reference source not found.**. The model determines the functional unit, which is expressed as the amount of hectares required to produce a kiloton of SAF. The main model input is the amount of produced SAF per day, which is a fixed value for each SAF production route. The conversion model determines the amount of feedstock required to produce the daily SAF production for each production route, by including the efficiencies of the conversion processes identified in the previous section. The required amount of utilities (hydrogen, heat and electricity) for each process is also determined.

The main difference between bio-SAF and e-SAF production routes is the carbon feedstock. Biomass (oil, sugar/starch and lignocellulosic crops) consists of large complex hydrocarbons which need to be broken down into smaller molecules (thermo)chemically and can only be harvested once a year. Therefore, large amounts of land are required to cultivate enough biomass for SAF production. In contrast, the feedstock of e-SAF production, CO2, is a simple molecule which needs to be upgraded to larger, complex molecules and can be collected from the atmosphere continuously. However, the processes within e-SAF production (CO2 capture, hydrogen production and the conversions into long-chain molecules) are energy-intensive, therefore requiring large amounts of electricity and land for solar and wind farms. Additionally, biomass feedstocks are easy and cost-efficient to store, but electricity, hydrogen and CO2 are not.

The total land use consists of the land required for biomass cultivation, DAC plant and the land required for utility production. Hydrogen is produced with electrolysis, which uses renewable electricity. Heat can be produced by heat pumps or by combustion of biomass or hydrogen. Heat pumps and hydrogen combustion also require renewable electricity to produce heat. Renewable electricity is assumed to be produced from a single hybrid solar and wind farm in each production route. These farms require land and are thus included in the total land use of each route. Land required by pre-treatment plants, SAF plants, electrolyzers and heat plants is not included, as it is expected that their impact is negligibly small.

Within the hybrid solar and wind farm, the solar panels are placed on the available areas between wind turbines to maximize land use efficiency. A combined bio-SAF and e-SAF route is also designed, where solar panels are substituted by biomass cultivation. This option is relevant to research, as the comparison between the combined route and individual e-SAF routes indicates if it is more land use efficient to use solar PV or biomass for SAF production. The combined route includes regular e-SAF production powered by wind turbines, along with the best performing bio-SAF production.

As all production routes produce useful co-products, LCA allocation methods are applied in the model. For instance, only a fraction of the rapeseed oil is converted into SAF, the other fraction is converted into other hydrocarbons. Therefore, only a fraction of the total land should be allocated to SAF production. Co-product allocation is generally done on the basis of product mass, energy content or economic value. As fuel products have different energy contents, allocation on the base of energy content is applied in this research. This is also a common approach in other LCA research on biofuels (Kim & Dale, 2002; De Jong et al., 2017; Niekurzak, 2021). Byproducts such as rape meal and DDGS are high in protein and can thus be used as animal feed. As these byproducts are used in a different end sector, a different allocation method is applied. This is done by allocation at the point of substitution, which refers to the co-product substituting another product, leading to avoided (environmental) burdens (Heijungs et al., 2021). In this research, rape meal and

DDGS can substitute soy meal as animal feed, which is a land-intensive product often related to environmental issues. The avoided burdens, the avoided land use for soy meal production in this case, are subtracted from the total land use of SAF production. A similar method can be applied in instances where SAF production routes produce net electricity, which can substitute electricity required in other processes outside of the scope of this research. By including these allocation methods, the total land use and functional unit can be determined for each production route. For the result section, land use breakdowns are constructed which indicate which processes, utilities or feedstocks are the most land-intensive for each SAF production route.

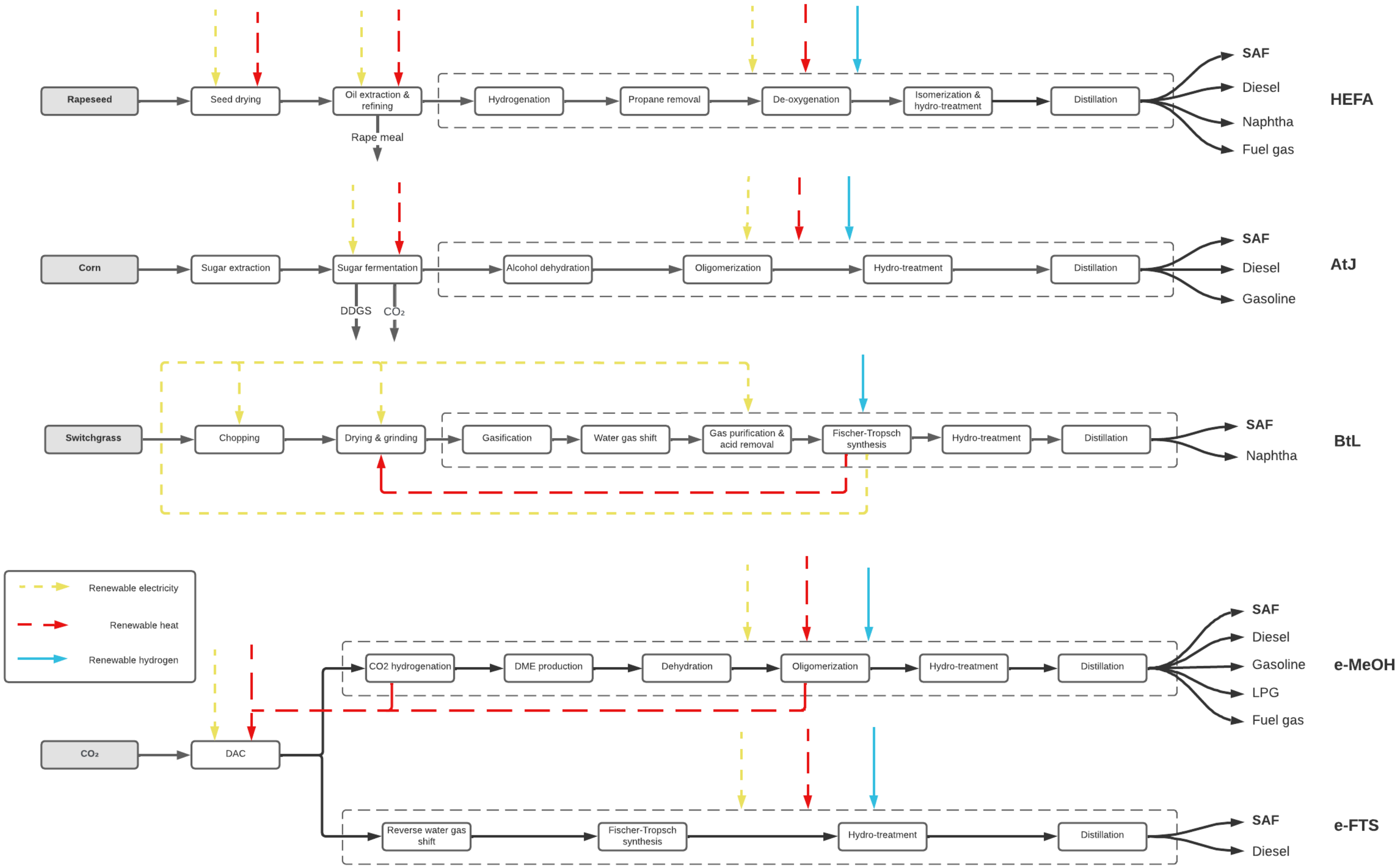

Figure 12 - Conversion model outline

3.2. Operationalization

3.2.1. Electricity production

All electricity consumed by the production routes is assumed to be produced by a combined solar and wind farm. The hybrid farm solely produces electricity for the bio-SAF or e-SAF processes, no other demand is fulfilled. The main input for the production routes is the electricity production potential, which is the amount of solar and wind energy which can be generated on a unit of land. These values are determined for both Spain and Poland, based on the annual electricity production of existing solar and wind farms in these countries. There is no findable data for combined solar and wind farms in these countries, so data on separate solar and wind farms is collected first and they are manually combined. Actual generation data of solar and wind farms is often not disclosed. Therefore, assumptions found in news articles and wind/solar farm reports are used. Production data of multiple farms is collected and combined into a database. The data of the best fitting solar and wind farms are taken for both Spain and Poland and combined into the electricity production potentials of hybrid farms.

The used data is annual and does not account for the varying volatility of solar and wind production. In reality, the production patterns of solar and wind energy vary across the year due to changing solar irradiation and wind speed, while the SAF conversion processes require a constant flow of electricity. Therefore, two scenarios are constructed for the supply and demand of electricity. In the optimistic scenario, it is assumed that the annual electricity production is evenly dispersed across the year and all produced electricity can be utilized by the conversion processes. The load factor of the SAF plant is not influenced by the electricity production of the hybrid farm. The option for battery storage is also added, where electricity can be stored temporary when production exceeds the demand. In the realistic scenario, it is assumed that the SAF plant only runs when the wind turbines or solar panels produce at full load. Therefore, the load factor of the SAF plant is equal to the load factor of the hybrid farm. In the situation that wind turbines and solar panels both produce at full load at the same time, it is assumed that a fraction of the electricity is curtailed. Therefore, the amount of electricity that can be utilized in the realistic scenario is substantially lower compared to the optimistic scenario. This method is also used by Fasihi et al. (2016) and Concawe (2022). The distinction between the optimistic and realistic scenario is only made for the e-SAF production routes, as the electricity requirement of bio-SAF routes is substantially lower. Only the optimistic scenario is included in the bio-SAF production routes.

The size values of production farms in terms of land are also collected. Land use data of solar farms is easily accessible, but there is no data for wind farms. Therefore, the investigated wind farms are looked up in Google Maps to measure the approximate surface area manually. As data is not available for combined solar and wind farms, a solar and wind farm array is designed based on the existing solar and wind farms. The array itself is based on research by Ludwig et al. (2020), see Figure 13. The area between turbines can be used for solar panels to increase the amount of electricity that can be produced on a unit of land, indicated by the blue area. Note that an area around the turbine cannot be used for solar PV production, as the wind turbine platform needs to be accessible for turbine maintenance. This area is also necessary to reduce shading on the solar panels caused by the turbine blades. The exact PV performance loss due to turbine shading is not clear at the moment, but Ludwig et al. (2020) does take shading into account.

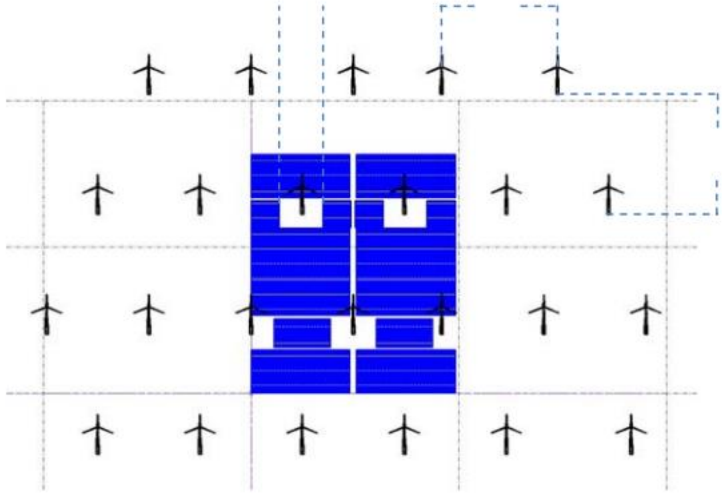

Figure 13 - Combined solar and wind farm array (Ludwig et al., 2020)

The electricity production potential of the wind turbines is calculated by dividing the annual production of the investigated wind farms by the approximate surface area of the wind farm. Some of the larger investigated wind farms are split into multiple smaller wind farms which are not located in the same array. However, the available annual production data for these large wind farms is for all wind farm arrays combined. In that case, the annual production of the whole wind farm is first divided by the total amount of turbines, providing the annual production per turbine. This value is multiplied with the amount of turbines in one array which surface area can be easily measured, to obtain more realistic data.

Next, the electricity production potential of the solar farm needs to be determined. Ludwig et al. (2020) have researched the required distance of solar PV racks from the turbine platform, which they relate to the rotor diameter. The larger the rotor diameter, the larger the distance between PV racks and turbine platform needs to be. Ludwig et al. (2020) assumes a distance between PV rack and turbine of 50 meters for a turbine rotor diameter of 82 meters, it is assumed that this is a linear relationship. By converting this data into a distance factor, the distance between PV rack and turbine is calculated for each investigated wind farm. Next, the unusable area per turbine and for the whole turbine array can be calculated. The unusable area per turbine is assumed to be a square area around the turbine, its area is calculated by doubling the distance between PV rack and turbine (providing either the length or width of the unusable area) and multiplying this value by itself to end up with the unusable area per turbine. The total available area is calculated as shown in equation (7).

$$available\ area_{PV}[ha] = area_{wind\ farm} - \left(n_{turbines\ in\ array} * (distance_{PV\ to\ turbine} * 2)^2\right) \qquad (7)$$

The electricity production potential of solar farms is calculated identically to that of wind farms. The surface area of the investigated solar farms are not manually measured, they are collected from the earlier mentioned news articles and/or solar farm reports. Next, the annual solar production of the PV panels in the combined solar and wind farm is calculated, taking into account performance loss due to turbine shading, see equation (8). All production values (MWh) are per year.

$$annual\ production_{PV\ in\ combined\ farm}[MWh] = EPP_{PV}\left[\frac{MWh}{ha}\right] * available\ area_{PV}[ha] * \left(1 - \frac{performance\ loss_{pv}(\%)}{100}\right) \qquad (8)$$

With EPP = electricity production potential

The total annual PV production needs to be converted into electricity production potential, but allocated to the surface area of the wind farm. Therefore, the annual production of the PV in the hybrid farm is divided by the area of the wind farm. Finally, the electricity production potentials of the solar PV and wind turbines are combined to end up with the total electricity production potential of the combined farm. In the optimistic scenario, a fraction of the produced electricity is lost due to the round trip efficiency of batteries.

The electricity loss due to battery storage is determined as shown in equation (9) and the electricity production potential for the optimistic scenario as shown in equation (10).

$$\begin{aligned}
&electricity\ loss_{battery}\left[\frac{MWh}{ha}\right] \\
&\quad = \left(EPP_{wind}\left[\frac{MWh}{ha}\right] + EPP_{PV}\left[\frac{MWh}{ha}\right]\right) * electricity\ stored[\%] \\
&\quad * \left(1 - \frac{\eta_{round\ trip}[\%]}{100}\right)
\end{aligned} \tag{9}$$

$$\begin{aligned}
&EPP_{hybrid\ farm,optimistic}\left[\frac{MWh}{ha}\right] \\
&\quad = EPP_{wind}\left[\frac{MWh}{ha}\right] + EPP_{PV\ in\ combined\ farm}\left[\frac{MWh}{ha}\right] \\
&\quad - electricity\ loss_{battery}\left[\frac{MWh}{ha}\right]
\end{aligned} \tag{10}$$

With $\eta_{round\ trip}$ *= round trip efficiency of the battery*

In the realistic scenario, a fraction of the produced electricity is lost due to curtailment. The electricity production potential for the realistic scenario is determined as shown in equation (11).

$$\begin{aligned}
&EPP_{hybrid\ farm,realistic}\left[\frac{MWh}{ha}\right] \\
&\quad = \left(EPP_{wind}\left[\frac{MWh}{ha}\right] + EPP_{PV\ in\ combined\ farm}\left[\frac{MWh}{ha}\right]\right) \\
&\quad * \left(1 - \frac{curtailment[\%\}}{100}\right)
\end{aligned} \tag{11}$$

3.2.2. Land use of SAF production routes

The first step is to determine the amount of feedstock required to produce the pre-determined amount of SAF. A capacity factor is included to account for the time in a year that the factory is not operating, necessary for maintenance for example. The amount of feedstock input is determined by taking into account all conversion efficiencies, from SAF distillation to feedstock pre-treatment. For bio-SAF and e-SAF, the feedstock input is determined as shown in equation (12). All mass values are per year.

$$biomass/CO_2\ feedstock[kt] = \frac{production_{bio/e-SAF}[ktSAF] * load\ factor[\%]}{\eta_{pre-treatment} * \eta_{core\ conversion}} \tag{12}$$

The land use of biomass and CO_2 is determined as shown as equation (13) and (14) respectively.

$$LU_{biomass\ feedstock}[ha] = \frac{biomass\ feedstock[kt]}{biomass\ yield\left[\frac{kt}{ha}\right]} \tag{13}$$

With LU = land use

$$LU_{CO_2\ feedstock}[ha] = \frac{CO_2\ feedstock[kt]}{DAC\ yield\left[\frac{kt}{ha}\right]} \tag{14}$$

The utilities of bio-SAF and e-SAF production routes consist of hydrogen, electricity, low temperature (LT) and high temperature (HT) heat. HT heat is characterized as heat requiring temperatures higher than 150 °C, LT heat is below 150 °C. This distinction is only made for e-SAF, where LT heat is produced by industrial heat pumps and HT heat by hydrogen combustion. The amount of hydrogen required for HT heat production is determined as shown in equation (15), where the HT heat requirement is divided by the product of the efficiency of the hydrogen boiler and the energy content of hydrogen. The heat required for bio-SAF is all produced by the combustion of low grade biomass, such as 2nd generation crops or residues (e.g. corn stover). The required amount of biomass is determined identically to hydrogen for HT heat production. The hydrogen required for the bio-SAF and e-SAF routes (including HT heat) is produced through electrolysis. The required amount of electricity is determined by multiplying the total required amount of hydrogen of a SAF production route with the electricity requirement of the electrolyzer. The industrial heat pumps which produce LT heat for the e-SAF routes also require renewable electricity. The electricity requirement is determined as shown in equation (16).

$$H_{2\,boiler}[kt] = \frac{HR_{HT,net}[MWht]}{\eta_{H2\,boiler} * energy\ content_{H_2}\left[\frac{MWht}{kt}\right]} \tag{15}$$

$$ER_{heat\ pumps}[MWh] = \frac{HR_{LT,net}[MWht]}{COP_{heat\ pumps}\left[\frac{MWht}{MWh}\right]} \tag{16}$$

The land use of the required biomass for heat production in the bio-SAF production routes is determined similar to the land use of the biomass feedstocks. If biomass residues are used (e.g. corn stover), no additional land use is included. The land use of electricity production is determined by first calculating the total electricity requirement of each production route and dividing this by the electricity production potential, see equation (17). The total electricity requirement consists of the net electricity requirement of the conversion processes (pre-treatment & core conversion), hydrogen production and heat pumps. The total land use of electricity is dependent on the choice of the optimistic or realistic scenario.

$$LU_{electricity}[ha] = \frac{ER_{processes,net}[MWh] + ER_{H_2}[MWh] + ER_{heat\ pumps}[MWh]}{EPP_{hybrid\ farm,realistic/optimistic}\left[\frac{MWh}{ha}\right]} \tag{17}$$

Next, the avoided land use resulting from substitution at the point of substitution is determined. First, the amount of obtained rape meal and DDGS is calculated from the amount of biomass feedstock. Rape meal and DDGS have less nutritious value (less protein) compared to soy meal, so a substitution factor on mass basis is applied to determine the amount of soy meal that is substituted. This is divided by the soy meal yield from soy beans, see equation (18). The total amount of substituted soybean is divided by the soybean yield to obtain the total amount of avoided land due to substitution. It is assumed that the soybean is cultivated in Brazil.

$$soy\ bean[kt] = \frac{byproduct[kt] * SF_{soy\ meal-byproduct}\left[\frac{kt\ soy\ meal}{kt\ byproduct}\right]}{yield_{soy\ meal\ from\ soy\ bean}[\%]} \tag{18}$$

With SF = substitution factor

The same method is applied when a production route produces net electricity. The net amount of electricity is divided by the electricity production potential to obtain the amount of avoided land for additional electricity production for other end uses.

The total land use is determined by adding up the land use of feedstock production (biomass or CO_2), electricity production (for process electricity, hydrogen or heat) and additional biomass feedstock for heat production. The avoided land use for feed or electricity production is subtracted from the total land use. As this land is also used for other useful co-products, the total land use is allocated to only the produced SAF. This is done by energy allocation of all useful co-products and their energy contents, see equation (19). The total energy content of the produced SAF is divided by the sum of energy contents of all useful co-products within the process, including SAF. This is multiplied with the total land use of the production route to obtain the allocated land use for SAF only.

$$LU_{SAF,allocated}[ha] = LU_{total}[ha] * \frac{production_{bio/e-SAF}[ktSAF] * energy\ content_{SAF}\left[\frac{MJ}{kt}\right]}{\sum production_{co-product}\ [kt] * energy\ content_{co-product}\left[\frac{MJ}{kt}\right]} \quad (19)$$

The final step is to construct the land use breakdowns, which shows the land uses of individual components within the production routes. By breaking the total land use down in components, the most land-intensive processes and utilities can be identified. This is done by calculating the land use of a single component, such as biomass cultivation or hydrogen required for the core conversion, and dividing by the total amount of produced SAF. As an abundant amount of electricity is required too, breakdowns are also constructed for the electricity requirement of each separate component.

3.3. Data collection

Only quantitative data is collected for this thesis. Most data is collected from academic studies using a techno-economic and/or life cycle analysis approach, for one of the five SAF production routes. Other data is obtained through free access models (mostly regarding e-fuel), models owned by the University of Utrecht and the remaining data is collected from news articles and free access databases (mostly 1st generation crop yields).

The vast majority of data is unique for each production route, but there is also data which is the same for all routes, see Table 1. The main input is the amount of SAF produced daily, or SAF throughput. The amount of SAF produced annually is determined by the throughput and the load factor, which is different for the optimistic and realistic route. Other data that is used in all production routes are technological parameters, such as the electricity consumption of the electrolyzer, the efficiency of the biomass and hydrogen boiler and the coefficient of performance (COP) of the industrial heat pump. Data for the allocation methods also falls under general data, such as the energy contents of co-products and soybean yield.

Table 1 - General input data

General data			
Production parameters	**Spain**	**Poland**	
SAF throughput	28.37 t/day		Zech et al., 2018
Load factor optimistic scenario	40 %		Assumption
Load factor realistic scenario	22.4 %	13.8 %	Calculations
Technology parameters			
Electrolyzer electricity consumption	53.4 MWh/t H_2		Oldenbroek et al., 2017
Biomass boiler efficiency	80 %		Gupta et al., 2022
Hydrogen boiler efficiency	80 %		Assumption
COP industrial heat pump	2.94		Lu et al., 2022
Allocation data			
Soybean yield	3.28 t/y		Ritchie et al., 2022
Soy meal yield from bean	0.8 t soy meal/t soy bean		Karlsson & Sund, 2016
Energy content SAF	43.9 MJ/kg		Blok & Nieuwlaar, 2020
Energy content diesel	43.4 MJ/kg		Blok & Nieuwlaar, 2020
Energy content gasoline	44.8 MJ/kg		Blok & Nieuwlaar, 2020
Energy content LPG	46.5 MJ/kg		Blok & Nieuwlaar, 2020
Energy content naphtha	44.9 MJ/kg		Engineeringtoolbox, n.d.
Energy content fuel gas	45.86 MJ/kg		Staffell, 2011

The input data for electricity production and the hybrid farm are shown in Table 2. The wind farms are located in Northern Spain (Aragon) and Northern Poland (Pomerania). These sites are selected due to the relatively high speeds compared to the rest of the country and as these farms have the best available data. The wind farms are shown in Figure 25 & Figure 26, see Appendix 3. The solar farms are located in the Southwest of Spain (Extremadura) and North of Poland (Pomerania). This Spanish solar farm is selected as it has the best available data of utility-scale solar farms in Spain, especially regarding land use. Although the solar farm is located in the Southwest (where higher solar irradiations are measured), the capacity factor is similar to large scale solar farms in Northern Spain. Wind farms with turbines of similar capacity are selected; the turbine capacity of the Spanish wind farm is slightly larger. However, larger wind turbines generally require more space compared to smaller turbines, so it is expected that the difference in capacity does not have a large impact on the land use of the electricity production. It is notable that the wind farms have similar capacity factors, but there are large differences in the capacity factor of solar farms. For the hybrid farm, the distance of PV panels to turbines is used to determine the amount of land which can be utilized by PV panels. The value in Table 2 is used to calculate a factor which is multiplied with the larger turbine diameters of the Spanish & Polish wind farms. In the combined bio-SAF and e-SAF route, the available land for biomass cultivation between the turbines is calculated the same as for solar PV in the other routes.

Table 2 - Input data for electricity production

Electricity production			
Wind farm	**Spain**	**Poland**	
Site selection	Phoenix (Aguillon)	Potegowo (Głuszynko-grapice)	
Total capacity	273 MW	55 MW	EVwind (2019); Power-
Capacity factor	42 %	40 %	Technology (2023)
Number of turbines	91	20	
Annual production	1000 GWh	192.3 GWh	Thinkproject (n.d.)
Turbine diameter	130 m	120 m	EVwind (2019); Power-
Turbine capacity	3 MW	2.75 MW	Technology (2023)
Number of turbines (for area calculation)	10	20	Google maps
Wind farm area (measured)	360 ha	600 ha	Google maps
Solar farm	**Spain**	**Poland**	
Site selection	Nunez de Balboa	Zwartowo	
Total capacity	500 MW	204 MW	Iberdrola (n.d.); Energy
Capacity factor	19 %	10 %	Institute (2022); Multiconsult
Annual production	832 GWh	178 GWh	(2022)
Solar farm area	1000 ha	311 ha	
Hybrid farm			
Distance PV to turbine	50 m for a turbine with diameter of 82 m		Ludwig et al., 2020
PV performance loss due to shade	1.7 %		Ludwig et al., 2020
Optimistic – electricity stored	20 %		Assumption
Optimistic – round trip efficiency battery	85 %		Cole & Frazier, 2019
Realistic – average annual curtailment	10 %		Fasihi et al. (2016); Concawe (2022)

3.3.1. *HEFA*

The input data for the HEFA production route is shown in Table 3. Rapeseed yields are collected from a database, where the average of the past five years are taken as input value. The rapeseed yield in Poland is slightly larger compared to Spain. Rapeseed contains a similar amount of oil and rape meal, the remaining mass in the rapeseed is water. The heat required for HEFA processes is produced by the combustion of switchgrass, of which the yield is higher in Spain compared to Poland.

The efficiency of the oil extraction during pre-treatment is 94 %. The pre-treatment consists of rapeseed drying, oil extraction and oil refining, which require electricity and a substantial amount of heat. The core HEFA process has an efficiency of 86.4 % and produces diesel, naphtha and fuel gas fraction aside from SAF.

Table 3 - Input data HEFA production route

HEFA			
Biomass cultivation	**Spain**	**Poland**	**Source**
Rapeseed yield	2.23 t/ha	2.76 t/ha	Ritchie et al., 2022
Oil content in rapeseed	0.44 t oil/t rapeseed		Stephenson et al., 2008
Rape meal content in rapeseed	0.47 t rape meal/t rapeseed		Stephenson et al., 2008
Substitution factor soy meal/rape meal	0.86 t soy meal/t rape meal		D’Avino et al., 2015
Switchgrass yield	10.21 t/ha	8.65 t/ha	Vera et al., 2021
Switchgrass energy content	16.2 MJ/kg		Mendu et al., 2011

Rapeseed pre-treatment		
Rapeseed oil extraction efficiency	0.94 t refined oil/t rapeseed oil	Gaber et al., 2018
Drying heat requirement	102.78 kWht/t rapeseed	Malca et al., 2014
Drying electricity requirement	5.56 kWh/t rapeseed	Malca et al., 2014
Extraction heat requirement	254.9 kWht/t rapeseed	Gupta et al., 2022
Extraction electricity requirement	43.9 kWh/t rapeseed	Gupta et al., 2022
Refining heat requirement	133.1 kWh/t rapeseed oil	Gupta et al., 2022
Refining electricity requirement	30 kWh/t rapeseed oil	Gupta et al., 2022
Core HEFA process		
HEFA fuel yield from rapeseed oil	0.864 t HEFA/t refined oil	Zech et al., 2018
SAF fraction in HEFA fuel	0.549 t SAF/t HEFA	Zech et al., 2018
Diesel fraction in HEFA fuel	0.104 t diesel/t HEFA	Zech et al., 2018
Naphtha fraction in HEFA fuel	0.285 t naphtha/t HEFA	Zech et al., 2018
Fuel gas fraction in HEFA fuel	0.063 t fuel gas/t HEFA	Zech et al., 2018
Hydrogen requirement	0.04 t H2/t rapeseed oil	Pearlson, 2011
Heat requirement	124.17 kWht/t rapeseed oil	Zech et al., 2018
Electricity requirement	37 kWh/t rapeseed oil	Zech et al., 2018

3.3.2. *AtJ*

The input data for the AtJ(+) production route is shown in Table 4. Corn plant yields are collected in the same manner as rapeseed yields. Spain has a substantially higher corn yield compared to Poland. Approximately half of the harvested corn plant weight is corn grain, the other half is corn stover. In the AtJ route, corn stover is combusted in a biomass boiler to produce the required heat. The remaining corn stover is not utilized for other purposes.

The efficiency of fermentation and ethanol production is 33 %. The byproducts are DDGS and CO_2. The substitution factor of DDGS is smaller compared to rape meal, as its protein content is lower. The efficiency of the core AtJ process is 60 %. The produced AtJ fuel consists of a large SAF fraction, but also a diesel and gasoline fraction. The AtJ process is split into alcohol separation and the core process due to the large energy requirement of the alcohol separation. This entails removing the remaining part of ethanol (and water) which is not converted into ethylene.

In the AtJ+ production route, all the carbon in the initial biomass input is utilized. Corn stover is first used to produce the required heat by combustion in a boiler. The remaining corn stover is dried, gasified and processed into additional bio-SAF through the BtL route. The captured CO_2 from ethanol production is fed into a RWGS reactor and is upgraded to e-SAF through FTS.

Table 4 - Input data AtJ(+) production route

AtJ			
Biomass cultivation	**Spain**	**Poland**	**Source**
Corn plant yield	11.71 t/ha	6.59 t/ha	Ritchie et al., 2022
Corn grain yield from corn plant	0.50 t corn grain/t corn plant		Farm energy, 2019
Corn stover yield from corn plant	0.50 t corn stover/t corn plant		Farm energy, 2019
Corn stover energy content	16.5 MJ/kg		Lizotte et al., 2015
Fermentation & ethanol production			
Ethanol yield from corn	0.33 t ethanol/t corn grain		Wang et al., 2015
DDGS yield from ethanol production	0.27 t DDGS/t corn grain		Wang et al., 2015
Substitution factor DDGS/soy meal	0.32 t soy meal/t DDGS		Wang et al., 2015
CO2 emission ethanol production	0.96 t CO_2/t ethanol		Own calculation based on molar masses
Fermentation heat requirement	1468.42 kWht/t ethanol		Wang et al., 2015
Fermentation electricity requirement	43.84 kWh/t ethanol		Wang et al., 2015
Dry corn stover yield from drying	0.833 t dry corn stover/t corn stover		Swanson et al., 2010
Corn stover drying electricity requirement	32 kWh/t feedstock		Hannula, 2016
Core AtJ process			
AtJ fuel yield from ethanol	0.6 t AtJ fuel/t ethanol		Geleynse et al., 2018
SAF fraction in AtJ fuel	0.7 t SAF/t AtJ fuel		Geleynse et al., 2018

Diesel fraction in AtJ fuel	0.2 t diesel/t AtJ fuel	Geleynse et al., 2018
Gasoline fraction in AtJ fuel	0.1 t gasoline/t AtJ fuel	Geleynse et al., 2018
Hydrogen requirement	0.0154 t H_2/t SAF	Geleynse et al., 2018
Alcohol separation heat requirement	4512.62 kWht/t SAF	Geleynse et al., 2018
Alcohol separation electricity requirement	61.73 kWh/t SAF	Geleynse et al., 2018
AtJ core heat requirement	3301.03 kWht/t SAF	Geleynse et al., 2018
AtJ core electricity requirement	449.6 kWh/t SAF	Geleynse et al., 2018

3.3.3. *BtL*

The input data for the BtL production route is shown in Table 5. The switchgrass yields are collected from the database of Vera et al. (2021). Spain has slightly higher switchgrass yields compared to Poland. The moisture content (and weight) is decreased by drying the switchgrass, which requires electricity.

The efficiency of gasification and FTS is 13 %. Not all the carbon content of the pre-treated switchgrass is converted into CO during gasification, a fraction of the carbon ends up in char and ash which are collected at the bottom of the gasifier. The char is fed into a cyclone and is combusted to provide the necessary heat to dry the switchgrass (Swanson et al., 2010). As FTS and other BtL processes do not require heat, there is no additional heat input required. The FT product consists mainly of SAF, a small fraction of naphtha is also produced. Unconverted syngas and fuel gas (one of the side products from FTS) are collected and fed into a gas turbine to produce electricity. It is assumed that this electricity can be used to power the other energy-intensive processes, such as air separation and syngas cleaning.

Table 5 - Input data BtL production route

BtL			
Switchgrass cultivation	**Spain**	**Poland**	**Source**
Switchgrass yield	10.21 t/ha	8.65 t/ha	Vera et al., 2021
Switchgrass pre-treatment			
Dry feedstock yield	83 wt%		Swanson et al., 2010
Pre-treatment heat requirement[a]	0 kWht/t dry switchgrass		Swanson et al., 2010
Pre-treatment electricity requirement	32 kWh/t dry switchgrass		Hannula, 2016
Gasification & FTS			
FT product yield from dry feedstock	0.13 t FT product/t dry switchgrass		Diederichs, 2015
SAF fraction in FT product	0.768 t SAF/t FT product		Diederichs, 2015
Naphtha fraction in FT product	0.232 t naphtha/t FT product		Diederichs, 2015
Hydrogen requirement	0.03 t H_2/t SAF		Diederichs, 2015
Electricity requirement ASU	1073.01 kWh/t SAF		Swanson et al., 2010
Electricity requirement syngas cleaning	259.41 kWh/t SAF		Swanson et al., 2010
Electricity requirement hydroprocessing	247.62 kWh/t SAF		Swanson et al., 2010
Electricity production gasification + FTS	3702.49 kWh/t SAF		Swanson et al., 2010

[a]Heat requirement is 0 kWh/t as the heat is provided by combustion of gasification products

3.3.4. *Methanol upgrading (E-MeOH)*

The input data for the e-MeOH production route is shown in Table 6. CO_2 is captured with DAC, which requires a substantial amount of (LT) heat and electricity. The efficiency of CO_2 hydrogenation to create methanol (MeOH) is 69 %. This process also requires a substantial amount of hydrogen, (LT) heat and electricity. The efficiency of the MTO/MOGD process is 44 %. Aside from SAF, the MTO/MOGD fuel mix also contains a diesel, gasoline, LPG and fuel gas fraction. A substantially smaller amount of hydrogen is required for the MTO/MOGD process compared to the CO_2 hydrogenation.

The e-MeOH production process requires two types of heat, LT heat for the DAC units (< 150°C) and HT heat (150 – 350°C) for the MTO/MOGD process. The HT heat is supplied by hydrogen boilers. CO_2 hydrogenation and the MTO/MOGD process both produce a substantial amount of LT waste heat in the form of steam, which can be used to provide heat for the LT DAC. The remaining heat demand is provided by LT industrial heat pumps which require electricity input.

Table 6 - Input data e-MeOH production route

e-MeOH			
LT DAC	**Spain**	**Poland**	**Source**
CO_2 yield	50064.70 t CO_2/ha		Ozkan et al., 2022
Heat requirement DAC (< 150°C)	3310 kWht/t CO_2		Sabatino et al., 2021
Electricity requirement DAC	720 kWh/t CO_2		Sabatino et al., 2021
Methanol production			
Methanol yield from CO_2	0.69 t MeOH/t CO_2		Meunier et al., 2020
Hydrogen requirement	0.203 t H2/t MeOH		Meunier et al., 2020
Electricity requirement CO_2 hydrogenation	387.8 kWh/t MeOH		Meunier et al., 2020
Heat production CO_2 hydrogenation (< 150°C)	330 kWht/t MeOH		Meunier et al., 2020
Methanol upgrading to SAF			
MTO/MOGD yield from methanol	0.4416 t fuel/t MeOH		Ruokonen et al., 2021
SAF fraction in MTO/MOGD fuel	0.27 t SAF/t fuel		Ruokonen et al., 2021
Diesel fraction in MTO/MOGD fuel	0.45 t diesel/t fuel		Ruokonen et al., 2021
Gasoline fraction in MTO/MOGD fuel	0.17 t gasoline/t fuel		Ruokonen et al., 2021
LPG fraction in MTO/MOGD fuel	0.04 t LPG/t fuel		Ruokonen et al., 2021
Fuel gas fraction in MTO/MOGD fuel	0.07 t fuel gas/t fuel		Ruokonen et al., 2021
Hydrogen requirement	0.0206 t H2/t SAF		Ruokonen et al., 2021
Heat requirement (> 150°C)	2264.04 kWht/t SAF		Ruokonen et al., 2021
Electricity requirement	320.22 kWh/t SAF		Ruokonen et al., 2021
Heat production (< 150°C)	6216.29 kWht/t SAF		Ruokonen et al., 2021

3.3.5. *Fischer-Tropsch (E-FT)*

The input data for the e-FT production route is shown in Table 7. Feedstock production (CO_2) is identical to the e-MeOH production route. The efficiency of the RWGS is 61 %. The process also requires hydrogen, HT heat and electricity. The efficiency of the FTS is 51 %. More than half of the FT product consists of SAF-range hydrocarbons, diesel makes up for the remaining fraction. FTS requires a substantial amount of hydrogen and some electricity. The production route does not produce waste heat, so all LT heat is produced by heat pumps and all HT heat by hydrogen combustion.

Table 7 – Input data e-FT production route

e-FT			
LT DAC	**Spain**	**Poland**	**Source**
CO_2 yield	50064.70 t CO_2/y/ha		Ozkan et al., 2022
Heat requirement DAC (< 150°C)	3310 kWht/t CO_2		Sabatino et al., 2021
Electricity requirement DAC	720 kWh/t CO_2		Sabatino et al., 2021
RWGS			
CO yield from CO_2	0.61 t CO/t CO_2		Terwel & Kerkhoven, 2018
Hydrogen requirement	0.07 t H2/t CO		Terwel & Kerkhoven, 2018
Heat requirement (> 150°C)	510.72 kWh/t CO		Terwel & Kerkhoven, 2018
Electricity requirement	110.90 kWh/t CO		Terwel & Kerkhoven, 2018
FTS			
FT product yield from CO	0.51 t FT product/t CO		Terwel & Kerkhoven, 2018
Jet fuel fraction in FT product	0.61 t SAF/t FT product		Terwel & Kerkhoven, 2018
Diesel fraction in FT product	0.39 t diesel/t FT product		Terwel & Kerkhoven, 2018
Hydrogen requirement	0.49 t H2/t SAF		Terwel & Kerkhoven, 2018
Electricity requirement	401.13 kWh/t SAF		Terwel & Kerkhoven, 2018

4. Results

4.1. Land use breakdowns

Figure 14 shows the land use breakdown of bio-SAF production routes. Biomass cultivation is the largest contributor to the total land use of the bio-SAF production routes. Heat, electricity and hydrogen demand are almost negligible, they are hardly visible in the land use breakdowns. Avoided land use for soy meal production due to feed substitution (either by rape meal or DDGS) does have a substantial impact on the total land use of the production routes. The net land uses of bio-SAF routes are indicated by the black triangles in Figure 14.

The net land use ranges from ± 400 ha/kt SAF for the AtJ+ production route in Spain, to ± 1350 ha/kt SAF for the AtJ production route in Poland. The other options have a land use between 600 and 1100 ha/kt SAF. The AtJ+ production route (Spain) scores best as all the carbon from corn is utilized and the yield of corn in Spain is the highest of all investigated crops. The inclusion of corn stover utilization and CCU leads to a land use efficiency almost twice as large as AtJ with just corn fermentation. The least land use efficient production route is the AtJ route in Poland, mainly due to low corn yields in the country. Poland shows potential for the HEFA production route, which is the second best bio-SAF production route in terms of land use. This is due to the high conversion efficiency of the HEFA route and large land substitution effect (caused by the high nutritious value of rape meal compared to soy meal). The substitution effect in the AtJ routes is smaller due to the lower nutritious value of DDGS. HEFA in Poland is more land use efficient than in Spain as rape meal yields are higher in the former country, unlike with corn cultivation. The HEFA production route requires a small amount of land for switchgrass cultivation, which is used for heat provision. This is not the case for the AtJ route, as a part of the corn stover is combusted to provide heat for the processes. The BtL route also does not require land for heat provision, as its processes only require electricity and hydrogen. BtL in Spain and Poland shows average results in terms of land use efficiency, switchgrass has relatively high yields in Spain and Poland but the conversion efficiency is the lowest of all production routes. The BtL routes produce surplus electricity in the gasification plant, but its substitution effect is negligible as this surplus is cancelled out by the additional electricity requirements for hydrogen production.

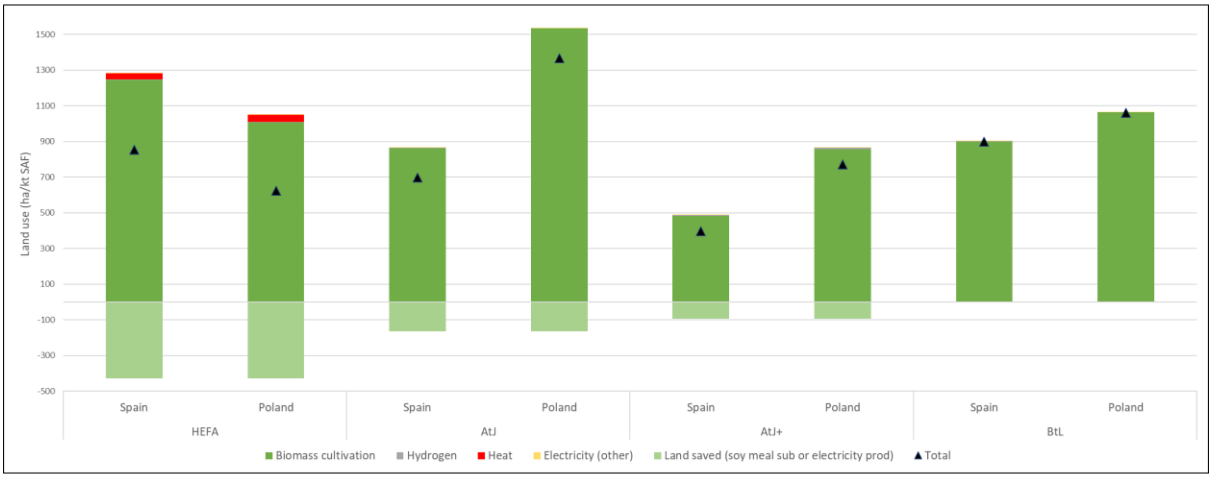

Figure 14 - Land use breakdown of bio-SAF production routes

The land use breakdowns of the e-SAF production routes are shown in Figure 15, only those in the realistic electricity provision scenario are shown. The differences between the scenarios are relatively small, the optimistic scenario shows slightly higher land use efficiencies for all production routes, see Figure 27 in Appendix 5. The realistic scenario is preferred over the optimistic scenario due to its more reserved assumptions in electricity supply. Similar to the results of the two scenarios, there are also small differences between the land use efficiencies of the e-MeOH and e-FT production routes. The e-SAF production routes range from 33 ha/kt SAF for the location in Spain to 42 ha/kt SAF in Poland. This is due to the larger electricity production potential, there is more solar irradiation in Spain. The e-MeOH route is slightly more land use efficient compared to the e-FT route. For both production routes, the electricity requirement for hydrogen production is the largest contributor to total land use, indicated by the blue segments in Figure

15. For the e-FT production route, the hydrogen land use of the FTS process is substantially larger than the hydrogen land use of the RWGS, due to its higher hydrogen requirement. The second largest is the heat demand, which consists of LT heat (for DAC) and HT heat for the core conversion processes. In both production routes, the LT heat requires more land than HT heat. The land use of DAC (the plant and the electricity requirement for DAC) is slightly smaller and the land requirement of electricity for the core processes (yellow segment) is almost negligible. The latter entails the electricity use required to power the main conversions of CO_2 into SAF. The land use of DAC is almost fully allocated to the electricity requirement of the DAC process, the impact of the DAC plant is negligibly small.

The combined route consists of the e-FT production route in combination with AtJ+, the best performing bio-SAF route. E-FT is chosen over e-MeOH in the combined route as the AtJ+ route also uses FTS. The land use of the combined e-SAF and bio-SAF is more than twice as high compared to the e-SAF only routes. Its land use ranges from 73 ha/kt SAF for Spain to 83 ha/kt SAF for Poland. Land use for hydrogen and heat production in the combined route is substantially higher compared to those of the e-SAF only route. Hydrogen and heat in the combined route are all produced with electricity. As there is no solar electricity included in the combined route, the electricity production potential is substantially lower compared to the hybrid farm of the e-SAF production routes. The combined route produces more fuel compared to the individual e-MeOH or e-FT route, but more land is required to provide the necessary utilities to produce the same amount of SAF. Approximately 75 % of the SAF is produced from CO_2 in the e-FT route, the other 25 % is produced from the corn and stover. As corn is grown on the land between the wind turbines with DDGS as byproduct, there is a decrease in total land due to the substitution of soy meal. Due to corn stover gasification, the production route also includes avoided land use for electricity production as electricity is produced from gasification products. However, both avoided land uses are not substantial enough to make the land use of the combined route competitive with the land use of e-SAF only.

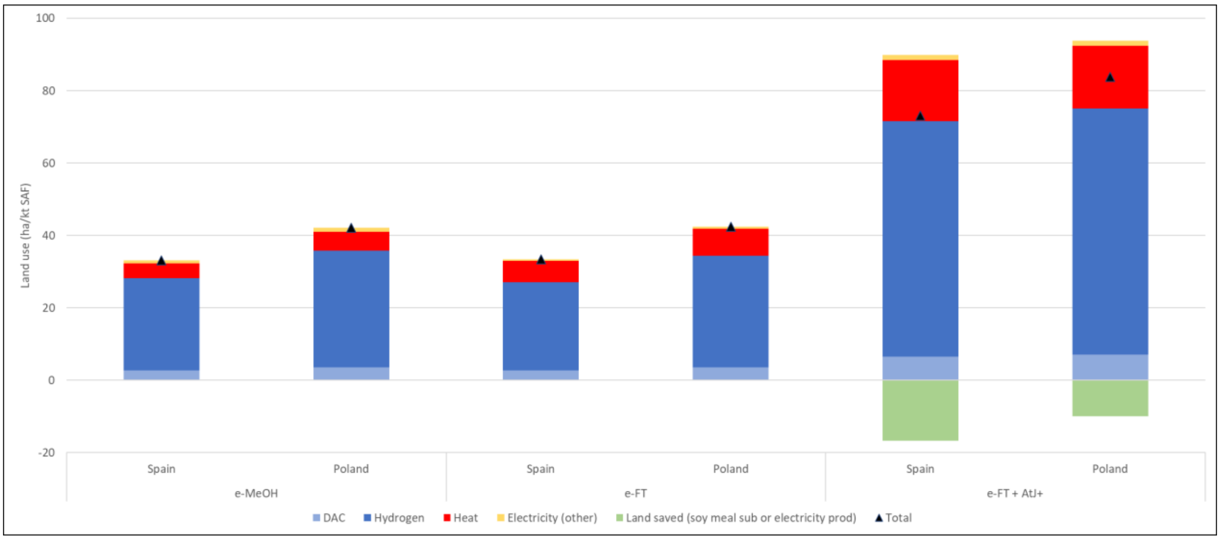

Figure 15 – Land use breakdowns of e-SAF production routes in realistic electricity provision scenario.

The results of the bio-SAF and e-SAF production routes in Figure 14 and Figure 15 respectively show that e-SAF routes are approximately 10-20 times more land use efficient than bio-SAF routes. The main driver for this substantial difference is the carbon feedstock for bio/e-SAF. Where biomass is harvest once a year and has relatively low yields, DAC continuously collects substantial amounts of CO_2 on a relatively small amount of land. The bio-SAF routes generally have higher conversion efficiencies from feedstock to SAF, but these do not outweigh the low feedstock yield per year. Hydrogen is by far the largest contributor to total land use of e-SAF routes, but its contribution is 20 to 30 times as small as the cultivation of biomass. AtJ+ in Spain has the lowest land use of all bio-SAF routes, which is a factor 10 larger than the land use of e-MeOH and e-FT route.

4.2. Electricity requirement breakdown

Although e-SAF production routes have substantially smaller land uses compared to bio-SAF routes, they do use large amounts of renewable electricity for especially hydrogen and heat production. As the demand for renewable electricity in most energy end sectors (e.g. transport, residential heating and power supply) increases, renewable electricity also becomes a scarce resource. An electricity requirement breakdown is shown in Figure 16. E-SAF routes require 5 – 30 times the amount of electricity compared to bio-SAF, depending on the production route. In all routes, hydrogen production is the largest contributor to total electricity consumption. Moreover, the electricity requirement of pre-treatment and core conversion is negligibly small. The AtJ+ route requires the most electricity of all bio-SAF routes, due to its additional hydrogen requirement for CO_2 upgrading to SAF through FTS. The AtJ route requires the least amount of electricity, the pre-treatment of corn and main conversions require substantially more heat compared to electricity. The BtL route requires more electricity than AtJ, but also produces electricity by combusting gasification products. The electricity production cancels out the electricity requirement, leading to a net electricity production in the full route.

The combined route of e-FT and AtJ+ requires the least amount of electricity per unit of e-SAF. The total electricity requirement of the combined route is larger compared to the individual e-SAF routes due to the added pre-treatment of corn and conversion into SAF, but the impact of this increase is relatively small compared to the additional SAF production. In all e-SAF routes, hydrogen production (also for heat) is by far the largest contributor to total electricity requirement. Where hydrogen required for pre-treatment (CO_2 hydrogenation) is the largest contributor in the e-MeOH route, hydrogen has a substantially larger impact in the core conversion (FTS) of the e-FT route. The share of DAC and LT heat in both production routes are substantially smaller, but still significant.

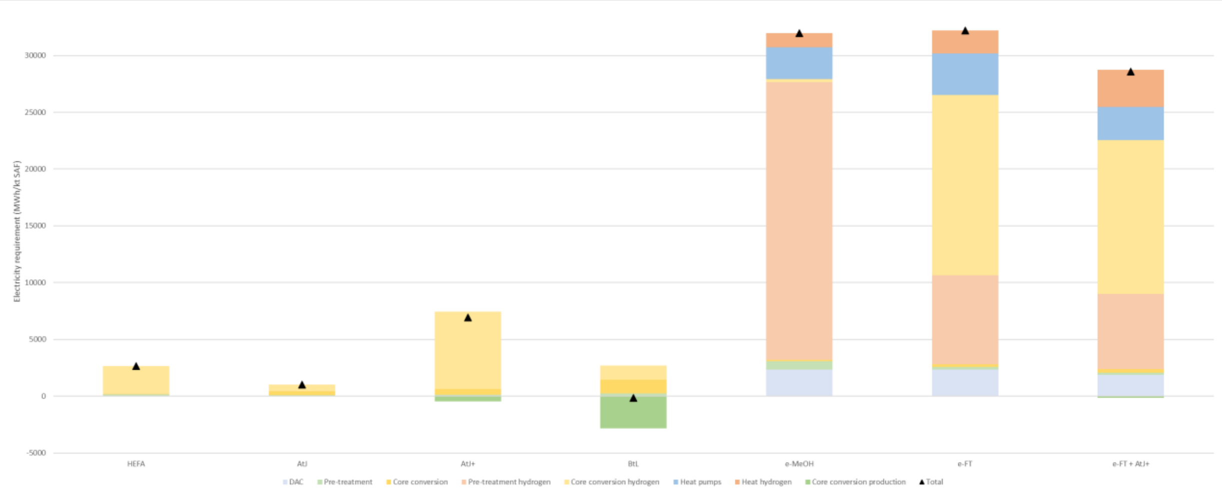

Figure 16 - Electricity requirement breakdown of bio/e-SAF production routes

4.3. Sensitivity analysis

The differences between the land use and electricity requirement of bio-SAF and e-SAF are evidently large, but the data and assumptions they are based on are uncertain. As most technologies and process combinations are novel and in need of more development, input data and results can deviate substantially from real data in the future. Therefore, sensitivity analyses are carried out for the most influential variables to indicate the robustness of the model and its input data. A range of values from different studies for the most influential variables is obtained during the desk research of this thesis. The ranges are shown in Table 8 in Appendix 4. The lowest and highest found values for each variable are taken as the boundaries for the sensitivity analysis. The black lines indicate the base value for each production route.

Land use of bio-SAF
The sensitivity analysis of land use of the bio-SAF production routes is shown in Figure 17. The biomass cultivation and conversion of biomass into SAF are the most significant contributors to land use of bio-SAF routes, so biomass yields and conversion efficiencies from feedstock to SAF are varied in the sensitivity analysis. The conversion efficiency is indicated by the orange bar, the biomass yield by the green bar and the combined effect by the black and white bar. The bars show how much the total land use of a bio-SAF route can vary by changing the base value of one variable to the maximum or minimum found value in literature.

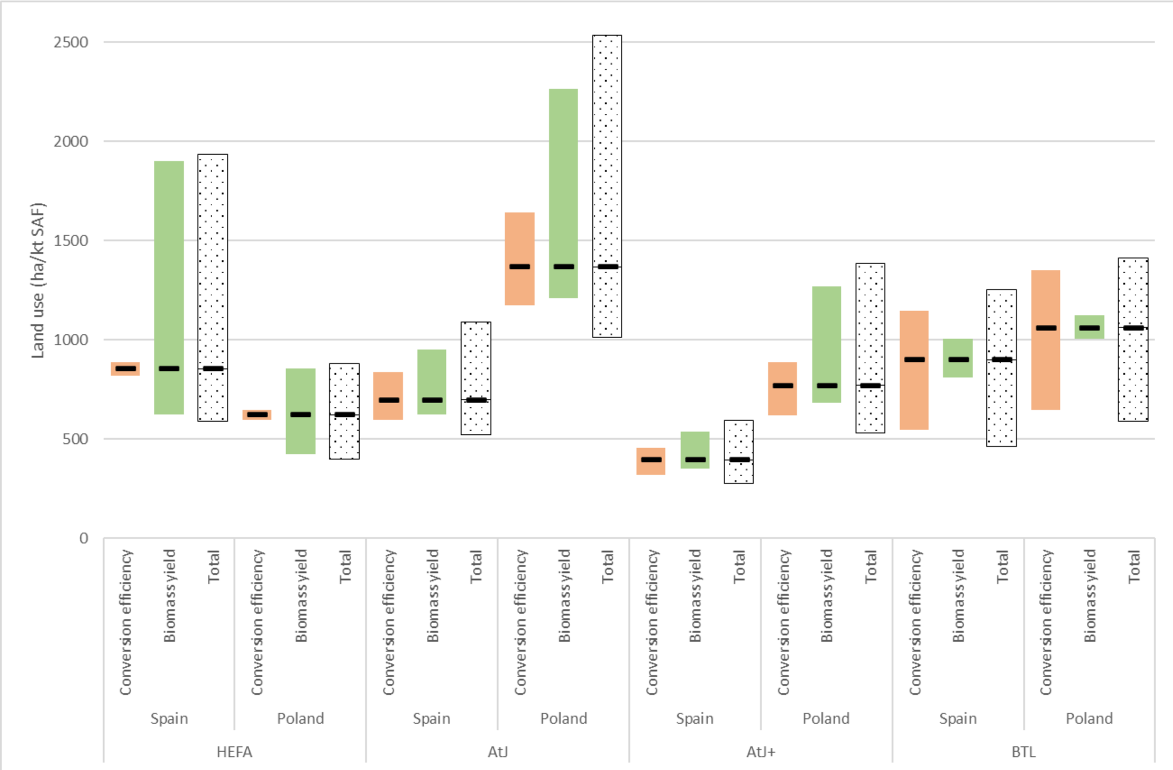

Figure 17 - Sensitivity analysis land use bio-SAF production routes

The total land use of HEFA is hardly influenced by varying the conversion efficiency, in both the case of Spain and Poland. The HEFA processes is the most mature and has the highest conversion efficiency of all production routes, so there are only small changes in conversion efficiency in literature. However, biomass yield has a large impact on the total land use, as rapeseed has the lowest yield of any biomass crop studied in this thesis. The lower boundaries of Spain and Poland show similar magnitudes of impact on total land use, but the high boundary of Spain is a lot more extreme. Rapeseed yields have varied substantially over the last few decades in Spain; the average yield in 2020 was 2.74 t/ha but only 1.21 t/ha in 2005. The latter yield is more than twice as small as the former, indicating the huge impact of a bad harvest year on the total land use of HEFA.

Varying conversion efficiency and biomass yield have a similar impact on the total land use of AtJ in Spain. The conversion efficiency variation is based on an assumed percentual change of ± 10 %, due to lack of data in literature. The biomass yield boundaries are based on the best and worst biomass harvest, similar to the HEFA route. The impact of biomass yield on the total land use of Poland has a larger impact compared to the conversion efficiency, especially the high boundary. Similar to rapeseed cultivation, this value is based on the worst harvest of the 21st century. If a bad corn harvest is combined with a lower conversion efficiency, the total land use in the Polish case almost doubles in size compared to the base value. This impact can also be seen in the Spanish case of HEFA.

The bar of conversion efficiency in the AtJ+ route contains the influence of the corn to SAF conversion efficiency, the corn stover to SAF efficiency and CO_2 to SAF efficiency. The impacts of the total conversion efficiency is smaller compared to the impact in the regular AtJ route, especially for Spain. This is also visible for the biomass yield and is due to the fact that the overall land use of the AtJ+ routes is smaller compared to the regular AtJ routes. With the most optimistic conditions, the total land use of the AtJ+ route in Spain can decrease to 275 ha/kt SAF. The AtJ+ route in Poland can also compete with HEFA in Poland an regular AtJ in Spain with the highest possible conversion efficiency and biomass yield. However, bad harvests have a substantial negative impact on total land use as well.

In contrary to the other routes, the conversion efficiency has a substantially larger impact on total land use in the BtL routes compared to biomass yield. The base conversion yield of the BtL route is the lowest of all bio-SAF routes but the possible minimum and maximum value differ substantially from the base conversion efficiency, while the base biomass yield is high for both Spain and Poland with minimal changes for the lower and higher boundary. This shows that the BtL route is mostly dependent on technological developments, and less on agricultural developments or occasional bad harvests. BtL in Spain is slightly more land use efficient and also has a competitive total land use when comparing to HEFA in Poland and AtJ(+) in Spain. Therefore, BtL is a good alternative to consider when 1st generation biomass cultivation for fuel production is not allowed due to policy restrictions for instance. This is especially true for Spain, as a substantial amount of marginal land could be utilized for the production of SAF.

Land use of e-SAF

The sensitivity analysis of land use of the e-SAF production routes is shown in Figure 18. Similar to the bio-SAF sensitivity analysis, the conversion efficiency is included. Other included variables are the electricity production potential of the hybrid farm (or only wind in the case of e-FT & AtJ+), electricity consumption of the electrolyzer and the amount of electricity curtailment. In the combined route, curtailment is included as electricity is only generated with wind farms. Instead, the corn yield is included as variable.

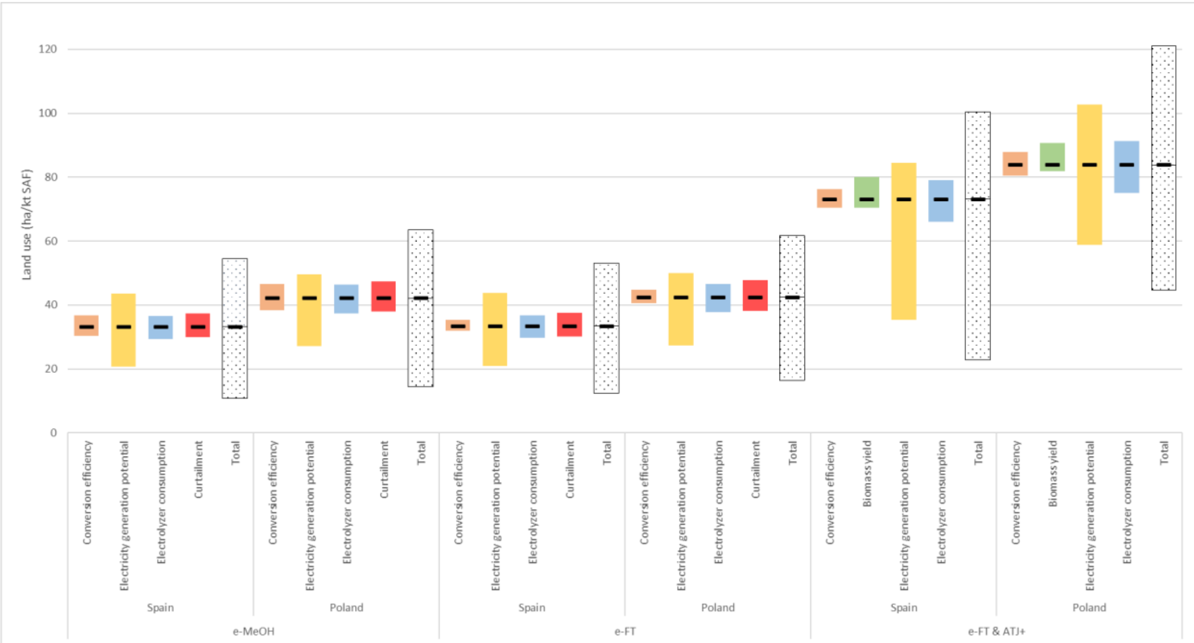

Figure 18 - Sensitivity analysis land use e-SAF production routes

It is visible that the sensitivity results of the e-MeOH and e-FT routes are quite similar for each country. The impacts of varying the conversion efficiency, electrolyzer consumption and curtailment are almost identical. The lower and higher boundaries have similar impacts on the total land use change, as they are based assumed percentual changes. This is the case for the conversion efficiencies and curtailment of the e-MeOH and e-FT routes as there is a lack of data in literature to create a range. The hydrogen consumption of the electrolyzer is not based on a percentual change but the optimistic and pessimistic value have similar distances to the base value. The electricity production potential is the largest contributor to total land use changes, caused by the divergent production potentials of the investigated solar and wind farms. In the most optimistic scenario, the e-MeOH route in Spain has the lowest total land use of 11 ha/kt SAF. This is 25 times as small as the land use of the AtJ+ route in Spain in the most optimistic scenario. The e-MeOH route in Poland has the lowest land use of 63.5 ha/kt SAF in the most pessimistic scenario.

The combined route shows similar results to those of the individual e-SAF routes. The variation in conversion efficiency and biomass yield have small impacts on the total land use. The impact of the electrolyzer consumption is slightly larger compared to the impact in the individual e-SAF routes, as additional hydrogen is required for the AtJ+ processes. The conversion efficiency only includes the efficiency of the e-FTS process, as the conversion efficiencies of the AtJ+ processes have small impacts on the total land use of the combined route. The variation in electricity production potential has the largest impact on total land use, especially for Spain. This is due to an outlier in the data, which is a wind farm that produces substantially more electricity per area unit compared to the other wind farms. However, this shows that larger and more efficient wind turbines can lead to large land use decreases in both the combined and individual e-SAF routes. The combined route in Spain can reach a land use of 23 ha/kt SAF in the most optimistic scenario, allowing it to compete with the individual e-SAF routes. The combined route is a viable option in areas where there is a relatively low solar irradiation, but high corn yield, such as

Germany. If 1st generation biomass cultivation is not an option, wind farms can also be combined with switchgrass cultivation and BtL as this bio-SAF route is a good alternative when utilizing marginal lands.

5. Discussion

Limitations and uncertainties

The main limitation of this thesis is the assumption that land is only used for one purpose; the production of SAF. This is especially true for the e-SAF production routes, which require substantial amounts of hydrogen, renewable electricity and heat. The model assumes that electrolyzers, hybrid farms, DAC units, heat pumps and boilers solely produce utilities for e-SAF processes, but these utilities are also used for other end uses in reality. For instance, electricity produced by hybrid farms is injected into national grids first and distributed to multiple sectors, instead of only being fed into the processes of an e-SAF plant. Bio-SAF has a similar situation, as 1st generation biomass is also used for food & feed and biomass can also be used for other energy end uses. The aviation sector is not the only sector that is difficult to de-fossilize. Renewable hydrogen and carbon (from biomass or DAC) are also required for the production of other chemicals and marine fuels. Therefore, other end uses will compete with SAF production in terms of (scarce) land and utilities, but the model does not address these issues.

Another limitation is the modelling of electricity supply and demand. In the optimistic scenario, the model assumes that the hybrid solar and wind plant can supply electricity to the SAF plant whenever it is needed. However, this assumption is unrealistic due to the volatile nature of solar and wind energy, which results in an inconsistent power output. In reality, multiple components of the SAF production routes require electricity at the same time, including DAC, pre-treatment, core processes, heat pumps and electrolyzers, which produce hydrogen for core processes and hydrogen boilers. The model simplifies the electricity provision and does not match the volatile production with the constant demand of the processes. Additionally, the model simplifies the modelling of individual components. In reality, electrolyzers run at a minimum load to retain safety, the quality of the hydrogen gas and conversion efficiencies. The same is true for DAC, as it is most cost-efficient to run DAC plants as much as possible. However, these principles are not applied as the model is not based on a time series. To address these limitations, the load factor of the e-SAF plant and its individual components is decreased to match the hybrid plant's load factor, and electricity curtailment is added to account for excess production. However, the model still lacks the capability to accurately match the supply and demand of electricity at each time, and the amount of curtailment is based on assumptions rather than empirical data. This is not implemented in the bio-SAF production routes, as they are substantially less dependent on electricity.

The electricity production potentials used for solar and wind farms are based on reported production data from news articles, instead of actual data. Real annual solar and wind output data is often not disclosed, which is also the case for the investigated areas of this thesis. Local differences in solar and wind potentials within countries are also not taken into account due to lack of data. The comparison of wind farms is also debatable, as the electricity production potential is highly dependent on the wind speed (which varies per location and hub height), type of turbine, the layout of the windfarm and how the occupied area of the wind farm is measured. The latter is measured manually with Google Maps, which is prone to human error and is debatable as other research could decide to include more or less land around wind turbines. Lastly, the potential of hybrid solar and wind farms is under debate, as the shadow of wind turbine blades could have an impact on the power output of solar panels. This thesis assumes the effect to be almost negligible, but few studies have been consulted for the combination of solar and wind energy. TNO is currently researching this effect, but results are not publicly available yet (TNO, 2021).

In addition to the limitations of the modeling aspect of this thesis, there are also limitations related to land use and its connection to the conversion model. While this thesis acknowledges the difference between arable and marginal land for fuel production, it does not provide a quantitative assessment of the available land for SAF production in Europe. Without this information, it is difficult to determine if there is enough land available in the researched countries and Europe as a whole to meet GHG emission reduction goals in the aviation sector. Furthermore, the land is also needed for feedstocks and production of other chemicals and marine fuels. However, rough estimates and recommendations for possible locations for SAF production in Europe are given.

Theoretical and practical implications

The results evidently show that e-SAF production routes use a factor 10-20 less land per unit of fuel compared to bio-SAF production routes. This is in line with prior studies such as Malins (2017) and Nova-Institute (2020), which claim that renewable electricity production (specifically solar) is substantially more land use efficient compared to the cultivation of biomass for fuel production. However, these studies only state the theoretical land use of e-fuels and biofuels, but fail to assess other aspects which are important to take into account when comparing e-fuels and biofuels. For instance, the results of this thesis show that the e-SAF production routes require a factor 5-30 more renewable electricity compared to the bio-SAF routes. Although the global installed renewable capacity is steadily increasing each year (IEA, 2021), it is struggling to keep up with the increasing electrification of demand (IEA, 2022b). Not only the electricity demand of SAF is expected to increase, substantial amounts of electricity will also be required for electric vehicles in the transport sector, heat pumps in the residential sector and energy-intensive processes in industry. The competition for renewable electricity leads to increased electricity prices (IEA, 2022b) which can subsequently lead to higher costs and slower developments of (especially e-) SAF.

Prior studies assume that e-fuel plant processes are continuously supplied by renewable power produced by solar and wind farms, but this is not a realistic scenario. In practice, e-fuel plants are in need of CO_2 and hydrogen storage (and possibly additional batteries) to ensure a constant fuel production and a full utilization of available electricity. This leads to increased complexity when it comes to the construction and efficient operation of a large scale e-fuel plant. Moreover, these implications also lead to substantially higher costs compared to biofuels, which are further in development. Most essential components of e-SAF production, such as DAC, electrolyzers and the e-fuel plant itself, are under development and will be for the next few decades.

Ultimately, the lower land use alone does not make e-SAF (and e-fuels in general) a better alternative compared to bio-SAF. In instances where little renewable electricity is available but surplus land is abundant, bio-SAF production routes could be a better option and vice versa for e-SAF production routes. E-SAF production routes are expected to see large developments in technology in the future, but de-fossilizing efforts in the aviation sector should be made in the meantime. Bio-SAF routes could serve as the necessary transition technologies in the next decades, especially in areas with available marginal and surplus land. HEFA and AtJ are the most promising as they have the lowest land use, but their performance are highly dependent on the location. Moreover, as much carbon as possible should be converted into useful products, as the AtJ+ route shows a substantial decrease in land use compared to the regular AtJ route. Aside from production routes with 1st generation feedstocks, the BtL route also shows good potential for SAF production. BtL is beneficial as many different feedstocks can be used, the route is less dependent on geographical location and marginal lands can be utilized. Towards 2050, e-SAF production routes could play a more dominant role as costs decrease and renewable electricity and hydrogen are more abundant. Routes which combine e-SAF and bio-SAF production are also expected to be promising, as these use less electricity in exchange for a slightly higher land use. This also includes a full utilization of marginal lands, by combining e-SAF production with bio-SAF production from 2nd generation biomass. In the end, the choice between bio-SAF and e-SAF is dependent on the choice between two scarce resources: land and renewable electricity. Future assessment of SAF production routes should be done on a case-by-case basis, as the use and availability of land and renewable electricity are highly dependent on location.

The question arises if enough land is available in Spain and Poland to produce enough SAF to meet current jet fuel and future SAF demand. The annual jet fuel demand in 2019 was 6900 kt in Spain and 1077[1] kt in Poland (Statista, 2023a; The Global Economy, 2021). In Spain, 2.7 million hectares are required to produce the jet fuel demand of 2019 with AtJ+ and 230 thousand hectares with e-MeOH. In Poland, 670 thousand hectares are needed with HEFA and 45 thousand hectares with e-MeOH. The amount of arable land in Spain is approximately 11.8 million hectares and 11 million hectares in Poland (Macrotrends, 2023a; Macrotrends, 2023b). The best performing bio-SAF production routes would require 22 % and 6 % of all agricultural land in Spain and Poland respectively, to fulfill the current jet fuel demand. The amount of marginal lands is assumed to be of equal size as arable lands. E-SAF production requires approximately 2 % of marginal land in Spain and 0.4 % in Poland. In both the bio-SAF and e-SAF case, there would theoretically be enough land. However, especially the scenario of bio-SAF is unlikely as arable land is also required for food production and other energy uses which require biomass feedstocks in the future. The report by E4tech (2021) states that 40 million ton SAF can be produced by 2050. If this demand would be supplied by bio-SAF in Spain or Poland alone, 15.5 million hectares of arable land is required in Spain or 24.4 million hectares in Poland. For e-SAF, 1.3 million hectares in Spain or 1.6 million hectares in Poland would be required, which are still significant quantities.

[1] The initial value is in thousand barrels jet fuel per day, this has been converted into kt jet fuel with a conversion factor mentioned in an article by BP (2021).

Future research

Future studies can build on the methods and results of this thesis in numerous ways. The main recommendation is to expand the modelling of electricity supply and demand of SAF production processes. A time series model is able to match hourly renewable electricity supply to the demand of multiple processes within a bio-SAF or an e-SAF plant. To ensure full utilization of the produced renewable electricity by solar or wind farms, hydrogen and CO_2 storages can be added, as well as additional batteries if required. Time series modelling does require specific input data for the demand of processes and supply by hybrid solar and wind farms, so specific locations with disclosed data need to be chosen. Aside from the assumption that all produced electricity is utilized by a SAF plant, a model could also be built where SAF is only produced when excess electricity is available, which would otherwise be curtailed. As electricity is also used for other end uses, this type of modelling creates a better reflection of reality. These two types of models also improve the determination of the capacity and the size of hybrid solar and wind farms, which is a substantial contributor to land use and total costs. It is expected that relatively more land is required for electricity production in these types of models, but the sensitivity analysis has shown that an increase in curtailment only slightly increases the total land use of e-SAF routes. Therefore, time series modelling will not turn the tide for bio-SAF when it comes to which production routes require the least amount of land.

Another recommendation is to include other types of renewable alternatives in aviation in the future, such as electric propulsion and hydrogen fuel. Although they are left out of this thesis due to low maturity, they are expected to play a role in time. Other important factors, such as costs and CO_2 emissions, have already been researched for bio-SAF and e-SAF. These studies can also be carried out for electric propulsion and hydrogen and their results can be combined with the findings of this thesis and prior research on bio-SAF and e-SAF for a complete and holistic outlook on sustainable aviation alternatives. Technical complexities and other environmental impacts, aside from GHG emissions, should also be included, such as water usage, air pollution and impacts on ecosystems et cetera.

The model could also be improved by expanding the scope of the SAF production chain, such as the feedstock production and transport. For instance, fertilizers and harvesting are left out of the model but have an impact on biomass yield, costs and the environment. Moreover, many more feedstocks and technology options can be included for the conversion routes. For instance, there are multiple 1st and 2nd generation feedstock which can be utilized, especially in other regions in the world. Sugar beet is excluded from this thesis due to the lack of data but generally has higher yields per hectare compared to corn, also in colder climates. Aside from BtL, 2nd generation feedstocks can also be used in the other production routes in the future, although these are not mature pathways. For instance, jatropha can be used in the HEFA route or lignocellulose can be converted into sugars and further processed into AtJ fuel. Other technology options can range from industrial electric (HT) heating, to other carbon capture technologies and less land-intensive electricity generation such as nuclear energy.

A final recommendation is to create a stronger link between the model and available land for SAF (and other renewable fuels/chemicals) production. In this thesis, the amount of land required for a certain amount of SAF production is determined. In future research, the amount of available land for SAF production can be quantified, after satisfying other demands such as food, feed, renewable power, electrified heat & transport and other renewable carbon-based fuels & chemicals. This should be studied by including other regions aside from Europe to assess global potentials, also taking into account possible (I)LUC and social issues, such as energy security.

6. Conclusion

This research has aimed to assess the land use of multiple production routes for bio-SAF and e-SAF in the EU, by building a model including all conversion processes and required utilities. Case studies for Spain and Poland are carried out, to indicate the influence of geographical location on the land use of SAF production.

The results show that e-SAF production routes are 10 – 20 times more land use efficient when comparing to bio-SAF routes. This large difference is due to the fact that biomass is harvested only once a year and has relatively low yields per hectare, while CO_2 capture by DAC and electricity production by hybrid farms can take place all year long. The e-MeOH production route has a land use of 33.19 ha/kt SAF in Spain and 42.14 ha/kt SAF in Poland, the e-FT route has a land use of 33.43 ha/kt SAF in Spain and 42.44 ha/kt SAF in Poland. The e-MeOH route is slightly more land use efficient due to higher conversion efficiencies and lower hydrogen requirements. The land use of e-SAF production in Spain is lower compared to Poland, as the hybrid solar & wind farm produces more electricity per hectare. Wind energy potentials of Spain and Poland are similar, but the solar irradiation in Spain is substantially higher.

For bio-SAF, the land use ranges from 395.62 ha/kt SAF for the AtJ+ route in Spain to 1368.02 ha/kt SAF for the regular AtJ route in Poland. The HEFA route in Poland and regular AtJ route in Spain have the most competitive land uses after AtJ+, at 622.50 ha/kt SAF and 697.43 ha/kt SAF respectively. These routes score best due to relatively high corn yields in Spain and high conversion efficiency of the HEFA conversion processes. The difference in land use of AtJ and AtJ+ shows the importance of fully utilizing all the carbon in the feedstock. The land use of bio-SAF routes is dominated by the land use of biomass cultivation, components such as hydrogen and other utilities have minimal impact. The sensitivity analysis also shows that a difference in biomass yield (due to bad or good harvest) has a substantial impact on the total land use. BtL is less influenced by differences in biomass yield, but land use can be decreased significantly if the conversion efficiency of gasification and FTS increases due to technological developments. The protein-rich co-products such as rape meal and DDGS also have a visible impact, they decrease the total land use of HEFA and AtJ(+) routes significantly.

E-SAF production routes are substantially more dependent on the production of hydrogen and electricity compared to Bio-SAF production. The vast majority of land use for e-SAF production is allocated to electrolyzers, along with energy requirements for DAC and heat supply. However, the land use of e-SAF production is quite robust, the land use only increases or decreases slightly with a difference in electricity production potential. While bio-SAF production cannot compete with e-SAF production when it comes to land use, the opposite is true for the total electricity requirement. E-SAF production routes require 5 – 30 times as much electricity compared to bio-SAF routes. The trade-off between land use and electricity requirements is important to make, as renewable electricity is expected to become a scarce resource and is not available in large quantities in all situations. The geographical location plays a significant role in the choice between bio-SAF and e-SAF production routes and in the overall debate of biofuels vs. e-fuels. Therefore, it is recommended to compare bio-SAF and e-SAF production routes on a case-by-case basis, by including costs, environmental impacts (not only GHG emissions), land use and technical feasibility. Although e-SAF production is more land use efficient, bio-SAF can function as a drop-in fuel the next decades as they are further in development and overall costs are lower. The best option is to produce AtJ(+) in the south of the EU, where biomass yields are highest and surplus land is abundantly available. Marginal lands can be utilized by cultivating multiple types of 2nd generation biomass as feedstock for the BtL route. Towards 2050, it becomes attractive to produce e-SAF due to technological developments in DAC and electrolyzers, along with cost reductions. Combined routes where both bio-SAF and e-SAF are produced are a viable alternative, as they require less electricity in exchange for a slight increase in land use.

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8. Appendices

Appendix 1 - prior research on EU surplus lands, biomass- and renewable electricity potentials

This appendix contains literature on land availability for fuel production in the EU, as well as biomass potentials. As the research is relatively old, there are not included in the main research. However, their findings have helped with the selection of regions that are used for the case studies of this research.

Ideally, fuel production takes place on the unused and abandoned agricultural lands in the EU. Some of these areas do need to be excluded due to prohibitions of socio-economic activities on protected lands or to remoteness of the lands, making socio-economic activities less attractive (European Commission, 2021). However, a substantial amount of marginal land could still be used for the production of 2nd generation biomass or renewable electricity. The cultivation of 1st generation biomass is expected to be less effective due to low soil fertility.

In addition to unused agricultural or marginal lands, so-called surplus land can also be used for the production of fuel. Surplus land can be defined as land which is left over after satisfying food and feed demand (Krasuska et al., 2010; Brinkman et al., 2018). Krasuska et al. (2010) states that surplus land can arise due to increasing crop yields for food and feed production and to decreasing population in some European countries. The expected shares of surplus land in the EU from this study are shown in Figure 19**Error! Reference source not found.**. Surplus land consists of fallow land, land currently used for energy crops and fertile land which has become available by removing food and feed crops.

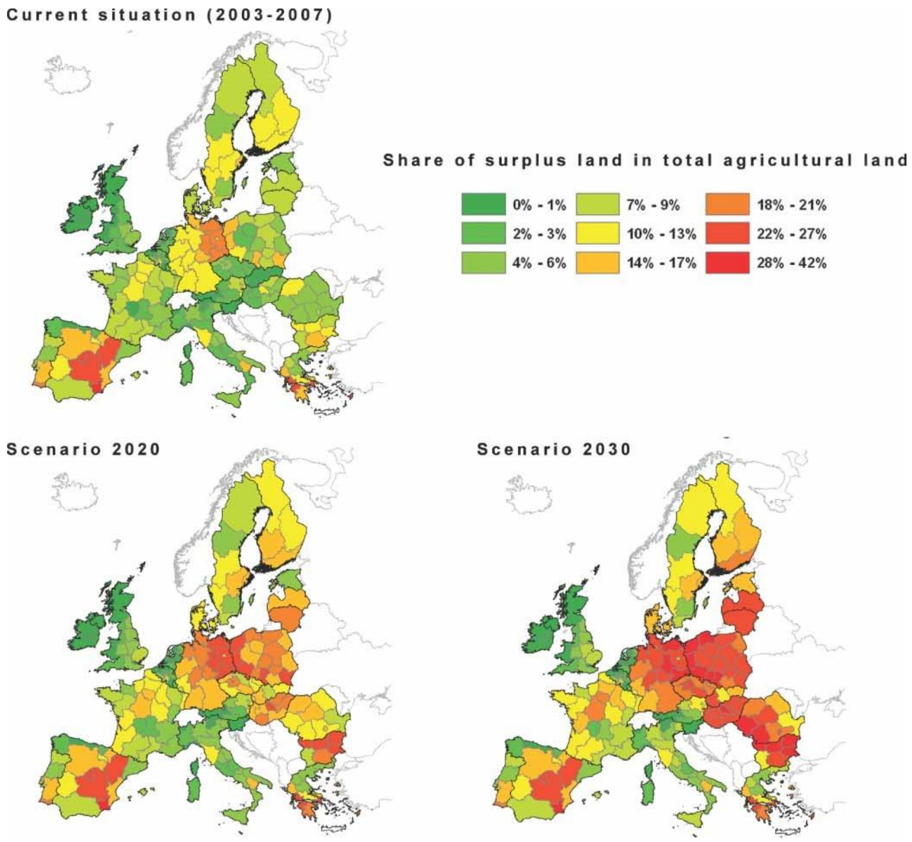

Figure 19 - Surplus land share of total agricultural lands in the EU (Krasuska et al., 2010)

Research by Allen et al. (2014) focusing on climate, soil and terrain constraints shows similar findings, see Figure 20. Productive agricultural areas have low to no constraints, indicated by the green areas which are similar to the results of Elbersen et al. (2018). However, the Baltics and Hungary show good potential on the map, unlike the findings of Elbersen et al. (2018). The eastern part of Croatia also suffers from no to few constraints for agriculture. In general, it can be seen that Spain, Greece and central Italy have high soil constraints, mostly due to mineral poor lands and drought. Large parts of the UK and Scandinavia also suffer from bad soil conditions, such as high acidity and too much water.

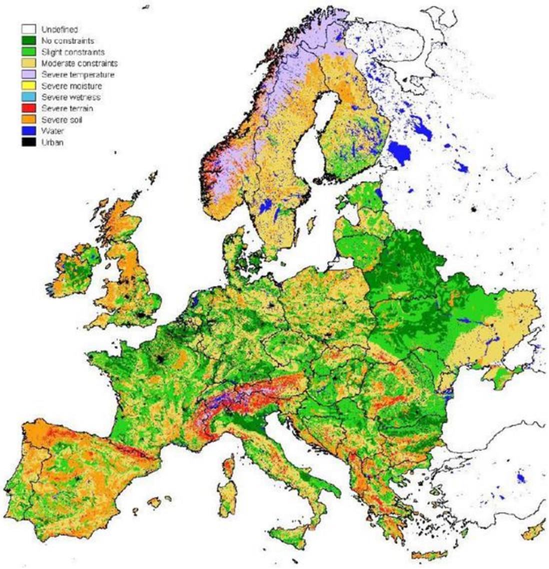

Figure 20 - Climate, soil and terrain constraints for rain-fed agriculture in Europe (Allen et al., 2014)

A third study by Fischer et al. (2010) has combined the quality of land, terrain and climate with crop yields of 1st generation biomass and fuel production efficiencies to obtain 1st generation biofuel potentials across Europe, see Figure 21. Fischer et al. (2010) characterized regions of European countries based on their soil fertility and climate to link them to a range of theoretical yields of sugar, starch and oil crops grown on surplus agricultural lands only. Similar to the findings of Elbersen et al. (2018) and Allen et al. (2014), the potential of 1st generation crops and related biofuel potential are low in large parts of the UK, Spain, central Italy, Scandinavia and Greece. The Baltic states perform worse in this study compared to the findings from Allen et al. (2014). Higher potentials are found in the Southwest of Spain & Portugal, France, Belgium, Germany, Poland, the Po valley, Hungary and Croatia.

When assessing 1st generation biofuel potentials, the influence of location of the yield of different biomass crops should also be taken into account. The most prevalent starch crops are cereals, such as wheat and maize. Sugar crops in the EU consist of sugar beet and sweet sorghum. Where wheat and sugar beet have the highest yields in countries such as France, the UK and the Netherlands, maize and (sweet) sorghum are preferably grown in warmer climates found in Spain, Italy and Greece (Ritchie et al., 2022). Spain is also an attractive country to cultivate sugar beets, as the Spanish sugar beet yield was the highest of all European countries in 2018 (CBS, 2019).

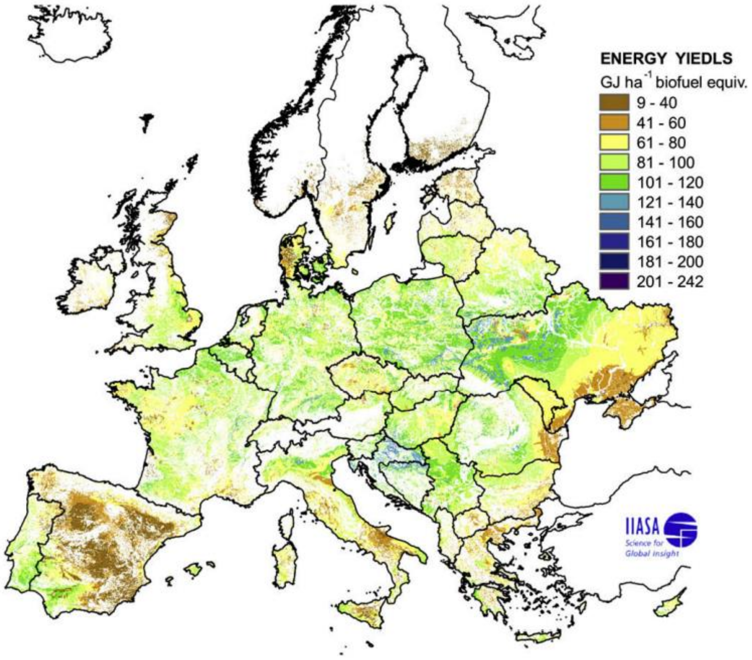

Figure 21 - Potential energy yields of 1st generation biofuels from feedstocks cultivated on surplus agricultural land (Fischer et al., 2010)

Fischer et al. (2010) also performed the same study for 2nd generation crops, see Figure 22. In general, it can be seen that theoretical energy yields of 2nd generation biofuels are larger compared to 1st generation biofuels. This is the case as more lands are available for production and high yields for 2nd generation biomass and high efficiencies of conversions into 2nd generation biofuels are assumed in the study. In practice, the potentials are expected to be lower as the conversion of 2nd generation biomass is energy-intensive, thus large amounts of additional energy are required.

In addition to surplus agricultural lands, 2nd generation feedstocks are also cultivated on pastures in Fischer et al. (2010). France, the Po valley in Italy, Croatia, Hungary, Lithuania and parts of Germany & Poland have the highest potential for 2nd generation biofuels. There is no mentioning of inclusion of marginal lands for biomass cultivation, but it is expected that this is left out of scope due to the low potential of lands in Spain and Greece.

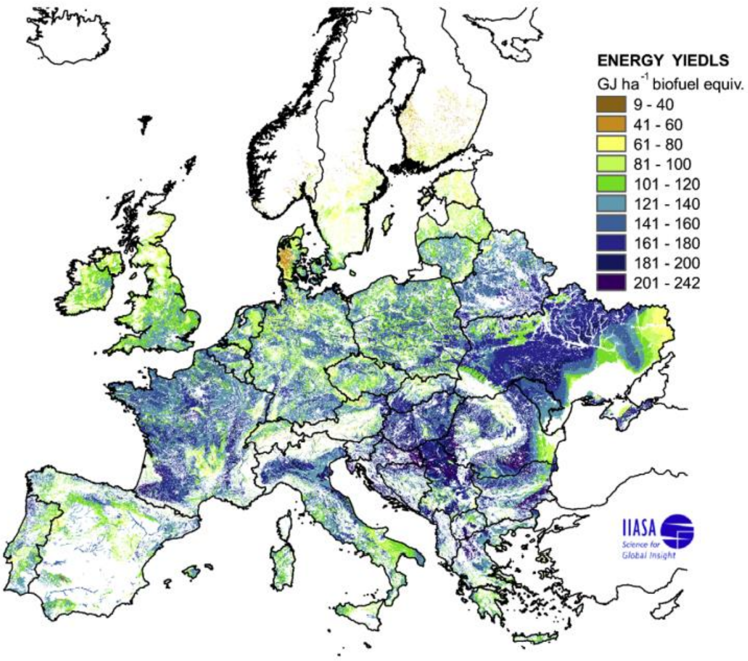

Figure 22 - Potential energy yields of 2nd generation biofuels from feedstocks cultivated on pastures and surplus agricultural land (Fischer et al., 2010)

Appendix 2 - Bio-SAF conversion pathways

This appendix includes the chemical reactions required for bio-SAF and e-SAF conversions.

HEFA

During hydrotreatment, the glycerides and FFA's are converted into alkanes in a few steps, see Figure 23. First, triglycerides (triolein, tripalmitin & trilinolein) are hydrotreated to saturate the natural occurring double bonds. In the case of triolein, 3 moles of H_2 are required to form stearine, a saturated triglyceride.

$$C_{57}H_{104}O_6\ (triolein)\ +\ 3H_2\ {-}{>}\ C_{57}H_{110}O_6\ (stearine) \qquad (20)$$

The saturated triglyceride is hydrotreated again to remove the glycerol backbone which breaks up the triglyceride into three FFA's. In the case of stearine, three moles of H_2 are needed to end up with three moles of stearic acid with propane as byproduct.

$$C_{57}H_{110}O_6\ (stearine) +\ 3H_2\ {-}{>}\ 3C_{18}H_{36}O_2\ (stearic\ acid) + C_3H_8(propane) \qquad (21)$$

The last step necessary to create alkanes is to remove the oxygen content from the FFA's, which can be with decarbonylation (removal of CO), decarboxylation (removal of CO_2) or hydro-deoxygenation (removal of H_2O). Hydro-deoxygenation is preferred, as this ensures the highest carbon efficiency and no carbon is emitted into the atmosphere (Neuling & Kaltschmitt, 2015; Starck et al., 2016; Wang & Tao, 2016; Tiwari et al., 2023). A range of C_{15}-C_{18} alkanes is produced, including octadecane.

$$3C_{18}H_{36}O_2\ (stearic\ acid) +\ 9H_2\ {-}{>}\ 3C_{18}H_{38}\ (octadecane) + 6H_2O \qquad (22)$$

The obtained mix of alkanes (also called linear paraffins) needs to be isomerized and hydrocracked as final step, requiring hydrogen and catalysts. Isomerization turns the long chain hydrocarbons (linear paraffins) into branched hydrocarbons (iso-paraffins) to reduce the freeze point, necessary to meet jet fuel A1 standards. Hydrocracking is applied to split the long chain paraffins into smaller chain paraffins, creating jet fuel similar to kerosine.

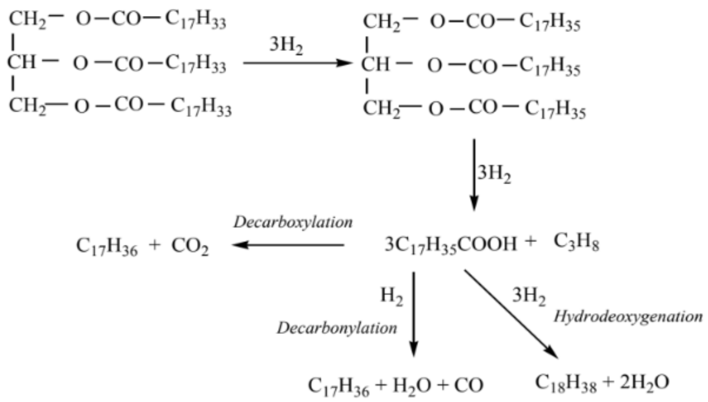

Figure 23 - Conversion of triglycerides to alkanes (Sotelo-Boyás et al., 2012)

AtJ

The fermentation reaction of ethanol is shown in equation (23).

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \qquad (23)$$

The ethanol is dehydrated next. Dehydration of an alcohol removes the water, creates a double bond between carbon atoms and converts ethanol into ethylene, the shortest chain alkene. Ethanol dehydration is sped up with catalysts and requires a temperature of ± 180 °C (Pechstein et al., 2018).

$$C_2H_5OH \rightarrow C_2H_4 + H_2O \quad (24)$$

Ethylene is then converted into longer chain alkenes (linear α-olefins) with oligomerization. For jet fuel, ethylene (C_2 alkene) is turned into alkenes with a carbon number between 8 and 16. Oligomerization also produces a variety of shorter chain olefins, which are not usable as jet fuel. The mixture is distilled to remove the short chain olefins, which are reused in the oligomerization process to end up with a higher share of jet fuel range olefins (Wang & Tao, 2016).

$$n[C_2H_4] \rightarrow C_{2n}H_{4n} \quad (25)$$

Alkenes/olefins are unsaturated hydrocarbons and cannot be used directly as jet fuel, due to their instability. The alkene mixture is hydrogenated to convert them into alkenes, with the use of catalyst at ambient temperature and pressure (see Figure 24). Finally, the alkane mixture is distilled and fractionated to end up with usable jet fuel.

$$C_nH_{2n} + H_2 \rightarrow C_nH_{2n+2} \quad (26)$$

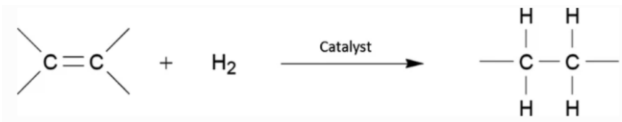

Figure 24 - Hydrogenation of an alkene (Pechstein et al., 2018)

BtL

After pre-treatment, the biomass enters the gasifier where it is pressurized and gasified with a mixture of pure oxygen and steam. The oxygen is obtained by feeding ambient air through an air separation unit, which splits the oxygen from the air mixture by using electricity. Steam is generated by heating water in a boiler, powered by produced syngas or additional biomass. During gasification, a mixture of CO, CO_2, H_2O, H_2, CH_4 and other CH molecules is formed by thermo-chemically breaking down (hemi)cellulose and lignin structures within the biomass.

$$Biomass + O_2 + H_2O(g) \rightarrow CO, CO_2, H_2O, H_2, CH_4 + other\ CHs + tar + char + ash \quad (27)$$

The specific composition of the syngas is dependent on multiple factors, such as the feedstock composition, moisture content of the feedstock and gasifier operation conditions. The gas contains multiple impurities after gasification which need to be removed, such as aromatic hydrocarbons, ash, tars and chemical compounds containing sulfur and nitrogen (Hu et al., 2012). The tar (long chain hydrocarbons) contains a substantial amount of CO and H_2, so it is usually cracked at high temperatures to increase carbon efficiency of the gasification (Hamelinck et al., 2004). After the impurities are removed, the H_2 to CO ratio is adjusted to the optimal FT ratio with the water gas shift (WGS) reaction (You & Wang, 2011).

The readjusted mixture of H_2 and CO is fed into the Fischer-Tropsch (FT) reactor, where they are combined to form a wide range of hydrocarbons, such as alkenes/olefins, alkanes/paraffins and other compounds like alcohol and aromatics (Wang & Tao, 2016). The desired FT reactions for alkanes/paraffins are shown in the equations below. The selectivity of products is highly dependent on the catalyst used, which is generally cobalt or iron. Unconverted syngas is recycled back into the FT reactor to increase desired product yield, the remaining gas can also be used for electricity generation necessary for the air separation unit (You & Wang, 2011).

$$CO + 2H_2 \rightarrow (-CH_2-) + H_2O \quad (28)$$

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + n(H_2O) \quad (29)$$

The initial share of kerosene/jet fuel range hydrocarbons can be increased by hydro-treatment, such as hydrogenation and hydro-cracking. During hydro-treatment, hydrogen reacts with longer hydrocarbons to split them into shorter chain alkanes. As final step, the mixture is distilled to end up with a mixture which fits the desired kerosene output profile.

Appendix 3 - Wind farm sizes Spain & Poland

As mentioned in the main research, the size of the wind farms of Spain and Poland are measured with Google Maps. In Figure 25 and Figure 26 the selected wind farms and their size are shown for Spain and Poland respectively.

Figure 25 - Wind farm Poland Głuszynko-grapice (part of Potegowo)

Figure 26 - Wind farm Spain Phoenix (Aguillon)

Appendix 4 – Sensitivity analysis input data

In Table 8 the sensitivity data for the bio-SAF and e-SAF production routes is shown. The low and high boundaries of the electricity production potentials are based on solar and wind farms that have the lowest and highest energy generation potential per hectare.

Table 8 - Input data for sensitivity analysis

Sensitivity data				
Conversion efficiency	**Low boundary**	**Base**	**High boundary**	**Sources**
HEFA	0.833	0.864	0.899	IATA, 2015; Pearlson, 2011
AtJ	0.5	0.6	0.7	Assumptions (± 10 %)
BtL	0.102	0.13	0.213	Diederichs, 2015; Dimitrou et al., 2018
e-MeOH	0.397	0.442	0.486	Assumptions (± 10 %)
e-FT	0.459	0.510	0.561	Assumptions (± 10 %)
Biomass yield Spain				
HEFA	1.21 t/ha	2.23 t/ha	2.74 t/ha	Ritchie et al., 2022
AtJ	9.04 t/ha	11.71 t/ha	12.83 t/ha	Ritchie et al., 2022
BtL	9.11 t/ha	10.21 t/ha	11.3 t/ha	Vera et al., 2021
Biomass yield Poland				
HEFA	2.24 t/ha	2.76 t/ha	3.44 t/ha	Ritchie et al., 2022
AtJ	4.16 t/ha	6.59 t/ha	7.35 t/ha	Ritchie et al., 2022
BtL	8.18 t/ha	8.65 t/ha	9.13 t/ha	Vera et al., 2021
General				
Electricity production potential Spain	739.78 MWh/ha	971.25 MWh/ha	1560.64 MWh/ha	Calculations
Electricity production potential Poland	649.27 MWh/ha	766.85 MWh/ha	1201.16 MWh/ha	Calculations
Electrolyzer electricity consumption	45.8 kWh/kg H_2	53.4 kWh/kg H_2	60 kWh/kg H_2	Oldenbroek et al., 2017
Curtailment	0 %	10 %	20 %	Assumptions

Appendix 5 – Additional results

This appendix includes some additional results for land use and sensitivity. They are not included in the main research as they do not add relevant information to the comparison between bio-SAF and e-SAF. Figure 27 shows the land use breakdown of production routes in the optimistic scenario. This figure shows almost identical results to the realistic scenario, therefore it has been left out of the result section.

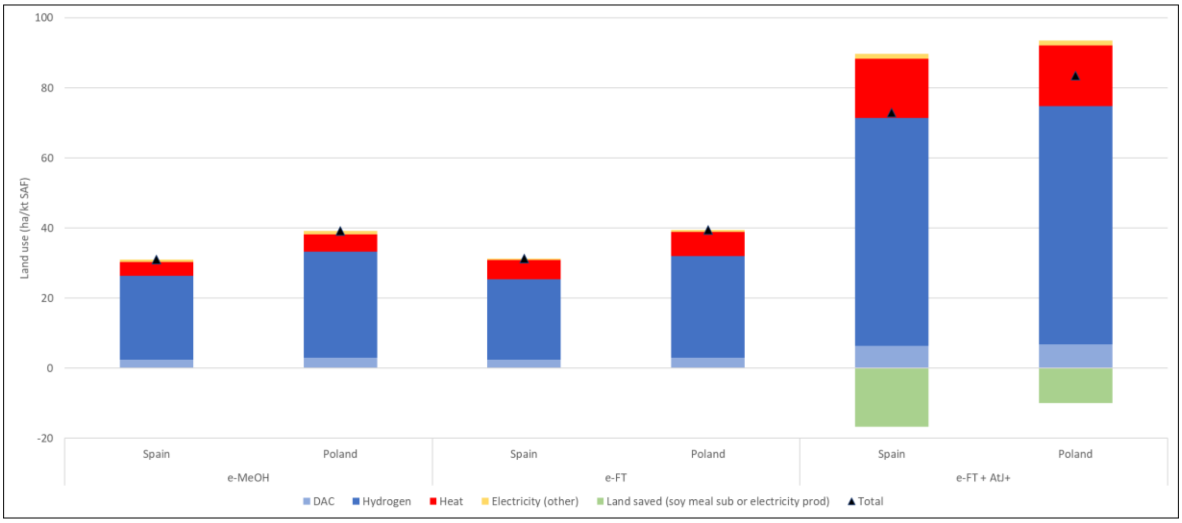

Figure 27– Land use breakdowns of e-SAF production routes in optimistic electricity provision scenario

As the electricity consumption of the electrolyzer is the largest contributor to total electricity requirement of all production routes, a sensitivity analysis has also been carried out by varying the hydrogen consumption of the electrolyzer, see Figure 28. It is visible that the electricity requirement of the bio-SAF routes are only slightly impacted by varying the electrolyzer consumption. For instance, the BtL route still has a net electricity production in the scenario with the highest electrolyzer consumption. The AtJ+ route shows the largest fluctuations due to added hydrogen requirements for the CO_2 conversion into SAF. The e-SAF routes are substantially more impacted by varying the electrolyzer consumption, but the ranges from the minimum to maximum bound seem smaller compared to those of the land use sensitivity analysis. In the most pessimistic scenario, the e-FT route has an electricity requirement 33 times as large as the electricity requirement of the regular AtJ route and 4.5 times as large as the AtJ+ route. This sensitivity analysis has been left out of the main research as it does not show huge differences between the lower and higher boundary.

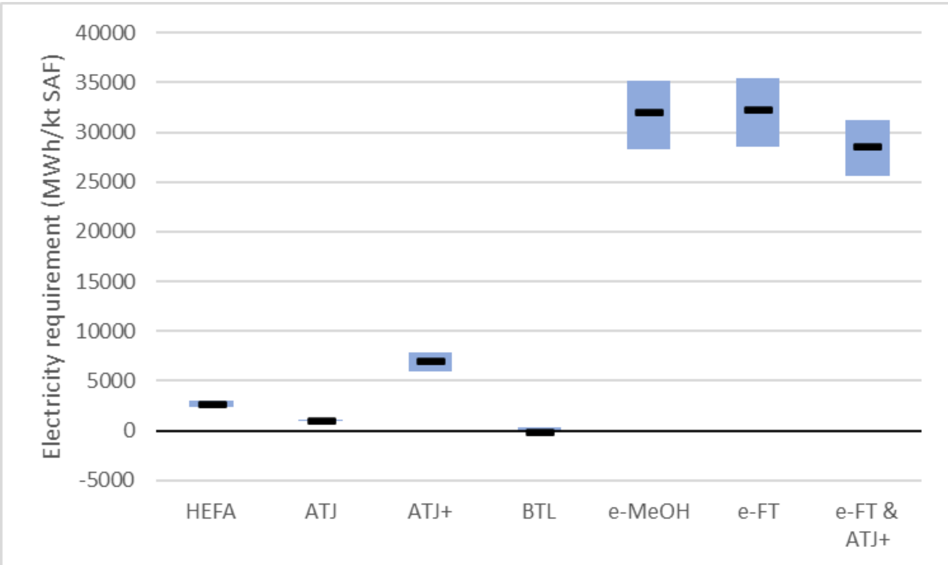

Figure 28 - Sensitivity analysis electricity consumption SAF production routes