BIOFUEL PRODUCTION FROM AGRICULTURAL WASTE

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Technology and Engineering Science, Bachelor's thesis

2024

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Examiner: D.Sc. (Tech.) Antti Pitkäoja

ABSTRACT

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Biofuel production from agricultural waste

Bachelor's thesis

2024

43 pages, 7 figures, 5 tables, and 4 formulas

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Keywords: biofuel, lignocellulose, bioethanol, biodiesel, Fischer-Tropsch, agricultural waste

This paper is written as a literature review of second-generation biofuels and the production methods behind them. Second-generation (2G) biofuels utilize non-food, lignocellulosic biomass. They offer a sustainable alternative to fossil fuels and can help combat climate change. Biofuels, in general, can be utilized in electricity generation, heating, and as a transport fuel in the aviation sector, road- and maritime transport. The thesis examines the challenges and opportunities associated with producing biofuels from agricultural waste and determines if it can be scaled up in the future. It also explores the potential applications and opportunities arising from technological advancements while addressing concerns regarding the technological, financial, and political barriers associated with large-scale production. The future of biofuels is still uncertain. There isn't a single definitive solution for the future of biofuels. The current use of biofuels is still heavily influenced by mandates, customs, and tariffs set by countries and varying entities.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Energiatekniikka

Aapo Hakkola

Biopolttoaineiden tuotanto maatalouden tähteistä

Energiatekniikan kandidaatintyö

2024

43 sivua, 7 kuvaa, 5 taulukkoa ja 4 kaavaa

Tarkastaja: TkT. Antti Pitkäoja

Avainsanat: biopolttoaine, lignoselluloosa, bioetanoli, biodiesel, Fischer-Tropsch, maatalouden jätteet

Tämä työ on kirjoitettu kirjallisuuskatsauksena toisen sukupolven biopolttoaineista ja niiden tuotantomuodoista. Toisen sukupolven biopolttoaineet hyödyntävät ruoaksi kelpaamatonta lignoselluloosapohjaista biomassaa. Ne tarjoavat kestävän vaihtoehdon fossiilisille polttoaineille ja voivat auttaa ilmastonmuutoksen hillitsemisessä. Biopolttoaineita yleisesti voidaan hyödyntää sähköntuotannossa, lämmityksessä sekä liikenteen polttoaineena lento-, maantie- sekä meriliikenteessä. Työ tarkastelee haasteita ja mahdollisuuksia, jotka liittyvät biopolttoaineiden tuottamiseen maatalouden jätteistä ja selvittää, voiko niiden tuotantoa laajentaa tulevaisuudessa. Työssä käsitellään myös, miten uudet teknologiset kehitykset voivat hyödyntää biopolttoaineita ja käsittelee suurimittaisen tuotannon mahdollisia ongelmia, kuten teknologisia, taloudellisia ja poliittisia esteitä. Biopolttoaineiden tulevaisuus on edelleen epävarma. Yhtä yksiselitteistä ratkaisua biopolttoaineiden tulevaisuudelle ei ole. Nykyistä biopolttoaineiden käyttöä ohjaavat edelleen vahvasti maiden ja eri tahojen asettamat määräykset sekä tullit.

ABBREVIATIONS

1G	First generation
2G	Second generation
3G	Third generation
IEA	International Energy Agency
EU	European Union
CO2	Carbon dioxide
CO	Carbon monoxide
AD	Anaerobic digestion
PPO	Pure plant oil
RME	Rape seed methyl ester
FAME	Fatty acid methyl ester
DME	Dimethyl ether
B100	Refers to the concentration of biodiesel in the blend
E85	Refers to the concentration of ethanol in gasoline (85 %)
CHP	Combined heat and power
FT	Fischer-Tropsch
GHG	Greenhouse gas
LCF	Low carbon fuel
ICEV	Internal combustion engine vehicle
FFV	Flex-fuel vehicle
SAF	Sustainable aviation fuel
MDO	Marine diesel oil

MGO	Marine gas oil
HFO	Heavy fuel oil
LNG	Liquefied natural gas
Mtoe	Megatons of oil equivalent
Mha	Mega hectare
R&D	Research and Development
BGY	Billion gallons per year
LCFS	Low Carbon Fuel Standard
RED II	Renewable Energy Directive II
EV	Electric vehicle

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1 Introduction

Biofuels have long been considered a promising alternative to fossil fuels as the world looks to move away from them. The first generation (1G) of biofuels was commercialized in the 1970s and was mostly produced from food crops like corn or sugarcane. The biggest producers then, and still are the US and Brazil by contributing 84% of the world's ethanol production in 2017 and 26% with biodiesel. (IEA, 2023.) Since the 70s, biofuels have undergone many technological advancements, such as the utilization of lignocellulosic biomass as a resource. This resource is both environmentally and ethically better than edible feedstock, and it is readily available, for example, from agricultural waste. Utilizing agricultural waste can help reduce the environmental impact and greenhouse emissions that the agricultural industry produces. Many countries are still dependent on foreign oil, and biofuels could help them improve their energy security (Prasad et al. 2023, Shadangi 2021).

Although first generation biofuels such as bioethanol offer an almost carbon neutral solution, they still require large amounts of natural resources like water and land for crop cultivation. Biofuels from lignocellulosic biomass don't utilize edible food and can be produced from agricultural, industrial or forestry waste. (Betiku et al. 2023)

Extensive research has been conducted on various biomasses and techniques for producing biofuels. Despite this, there are some challenges in scaling up biofuel production from various kinds of waste, such as costs of preprocessing and complex conversion techniques. (Naik et al. 2010)

The purpose of this bachelor's thesis is to examine the challenges and opportunities associated with producing biofuels from agricultural waste and determining if it can be scaled up in the future. The thesis provides an overview of first- and second-generation biofuels (1G and 2G biofuels), including their production methods such as fermentation, pyrolysis, and gasification, as well as their general applications. The last two chapters consider and reflect on some of the technological, social and political challenges that need to be overcome to scale up biofuel use even more. The study focuses more on the 2G of biofuels and their application but reviews briefly the 1G biofuels, their background and production. The study doesn't focus on the third or fourth generation biofuels as they are not yet commercially available and are not directly produced from agricultural waste or byproducts. After reading this study, the reader will have an understanding on what types of biofuels are there, how can they be produced and used, and what opportunities and challenges they face.

2 Biofuels

Biofuel is a renewable energy source which is made from organic materials (plants, crops or waste). These materials go through different processes to transform to usable fuels. Plant biomass also can be used to produce heat and electricity by burning it. When plant biomass is burned it releases the same amount of CO2 as it has used through photosynthesis. Biofuels can serve as an alternative for fossil fuels to promote sustainable energy production and contribute to mitigating climate change. (Naik et al. 2010.)

2.1 Categorization of biofuels

Biofuels can generally be categorized into three different categories, first-, second- and third generation. The production of the 1G biofuels typically involves utilizing materials that could be used for food for example sugar cane, corn and potatoes. By processing them we can produce ethanol and fatty acid methyl ester. Biogas can also be produced from them by a method called anaerobic digestion (AD). (Zhang, 2010)

Unlike 1G biofuels, second generation biofuels don't use edible feedstocks as the primary source for biofuel production. They involve complex processes and often involves converting lignocellulosic biomass into fuel. (Naik et al., 2010)

Third generation (3G) biofuels are made from algae. Algae is an aquatic plant that can grow on both saltwater and freshwater, it is a promising source for the future since it has the potential to produce more biomass per area than terrestrial biomass. However, 3G biofuels are still relatively expensive and challenging to produce in a bigger scale. (Lackner, 2021)

2.2 First generation

1G biofuels first started growing on the twentieth century. It was noticed that the burning of fossil fuels and the increase in the level of C02 emissions were linked. The risen costs of oil prices have enabled liquid biofuels to be established and fully commercialized. As fuels they are characterized how well they blend with petroleum-based fuels, or how well do they fit into the petroleum-based fuels infrastructures, piping and combustion engines. The biggest downside is seen to be the use of edible food for the fuels. That has created some issues including the rise of food prices and the ethicality question regarding the "food-versus-fuel debate". (Naik et al. 2010) In Table 1 below, the most common 1G automotive biofuels are classified.

Table 1. Classification of 1G automotive biofuels. (Zhang, 2010, EU Biofuels Advisory Council, 2006)

Biofuel type	Specific names	Biomass feedstock	Production process
Bioethanol	Conventional bioethanol	Sugar beet, grains	Hydrolysis, fermentation
Vegetable oil	Pure plant oil (PPO)	Oil crops (rape seed)	Cold pressing/extraction
Biodiesel	Biodiesel from energy crops Rape seed methyl ester (RME), fatty acid methyl ester/ethyl ester	Oil crops (rape seed)	Cold pressing/extraction & transesterification
Biodiesel	Biodiesel from waste FAME/FAEE	Waste/cooking/frying/ oil/animal fat	Transesterification
Biogas	Upgraded biogas	Wet biomass	Digestion
Bio-ETBE		bioethanol	Chemical synthesis

2.2.1 Bioethanol

1G bioethanol is typically produced from feedstocks that are based on starch or sugar, such as sugar cane and corn. The United States and Brazil are the biggest producers of ethanol globally, which makes over 80% of its production. In the United States, ethanol is mainly produced from starch-based plants using either a wet-milling or a dry-milling process. On the other hand, Brazil, which is the second-largest ethanol producer in the world, produces ethanol from sugar-based feedstocks. (Hoang et al. 2021.) The world's biggest ethanol producers between 2018-2020 are illustrated by millions in Table 2.

Table 2. Annual world fuel ethanol production in millions of liters. (Hoang et al. 2021)

Region	2018	2019	2020	% of world production (2020)
United States	16,091	15,778	13,926	53%
Brazil	7990	8590	7930	30%
EU	1450	1370	1250	5%
China	770	1000	880	3%
Canada	460	520	428	2%
India	430	510	515	2%
Thailand	390	430	400	2%
Argentiina	290	280	230	1%
Rest of the world	529	522	500	2%
Total	28,400	29,000	26,059	

2.2.2 Biodiesel

Biodiesels are defined as renewable fuels that can be produced via four different pathways, blending with vegetable oils, transesterification, microemulsions, and pyrolysis. It consists of fatty acid methyl esters and is also known by the name "FAME". Raw materials for 1G biodiesels usually come from different fats and oils. Second generation biodiesels tend to use waste oils, animal fats, and any oils that aren't edible. Although biodiesels have their disadvantages including their high production cost, they have benefits such as biodegradation, reduced toxicity, and lower emission profile. (Abbaszaadeh et al. 2012).

In transesterification, fatty acid alkyl esters are produced by using a catalyst to get the triglycerides from oils or fats to react with alcohols. The byproduct of the process is glycerine. Abbreviations are often used for transportation fuels, such as B100 which refers to the amount of biodiesel in the fuel. In the case of B100, it is 100% FAME, whereas B20 has a lower concentration of biodiesel in it and can be only considered a biodiesel blend. (Hoekman et al. 2012.) Biodiesels have varying properties depending on the feedstock they are made of. They also have differing properties compared to petroleum-based diesels. Cetane number, cold-flow properties, oxidative stability and lubricity have all conflicting effects on the fuel performance, and it makes it difficult to determine an optimal balance between all the properties. Cetane number is an indicator of how the fuel burns during combustion in the engine. With higher cetane numbers, the fuel tends to burn more quicky and with shorter ignition delays. This number is determined by comparing the blend of cetane and isocetane and calculating a volume-weighted average of the two. (Hoekman et al. 2012)

2.3 Second generation

Even though biofuels can be categorized into different generations, there are no legal implications associated with these categories. The categorization simply makes it easier to differentiate between biofuels made from edible and non-edible feedstock. (Abbaszaadeh et al. 2012.) Raw material for second generation biofuels is lignocellulosic biomass. It has several advantages over other resources. It can be found in the form of agricultural waste, paper industry waste and byproducts, wood waste, and landscape waste. These materials are inexpensive and readily available, and many of them can even generate fees for their disposal. (Blaschek et al. 2010.)

2.3.1 Agricultural waste and lignocellulosic biomass

Agricultural wastes are often left to the environment, contributing negatively to animal and human health. Converting this waste toward sustainable fuels could be environmentally and financially beneficial. (Betiku et al. 2023.) After the harvest of crops, agricultural materials are available, and their residues contain cellulosic material. If they are not returned to the soil, they can be used to produce biofuels. Similarly, animal wastes are also high in cellulosic material and have potential for biofuel production in the future. (Blaschek, 2010)

Lignocellulosic biomass consists of three different polymers, cellulose, hemicellulose and lignin. Cellulose is found in the wall of the plants cell and is one of the abundant and important natural polymers in the plant world. It is that because it holds approximately 40% of the carbon attached to living organisms (about 270 000 megatons). Typically, lignocellulosic biomass contains cellulose the largest amount, the second largest amount is hemicellulose and the third is lignin. Table 3 shows how much different plants contain cellulose, hemicellulose and lignin. (Shadangi, 2021)

Table 3. Lignocellulosic biomass compositions (% dry basis). (Ragauskas, 2014)

Feedstock	Cellulose	Hemicellulose	Lignin
Pine	43.3	20.5	28.3
Spruce	45.0	22.9	27.9
Douglas fir	45.0	19.2	30.0
Poplar	44.7	18.5	26.4
Eucalyptus	49.5	13.1	27.7
Corn stover	36.8	30.6	23.1
Miscanthus	39.8	24.8	22.7
Wheat straw	42.1	23.8	20.5
Switchgrass	42.0	25.2	18.1

2.3.2 2G Bioethanol

To produce 2G bioethanol, a pretreatment process is required, unlike 1G bioethanol. The process involves three main steps: delignification, depolymerization, and enzymatic fermentation. Delignification is used to separate hemicellulose and cellulose from lignin. When the lignin is removed, halo-cellulose, (which are polysaccharides in the plant cell wall), can then be hydrolyzed into smaller parts, C5 and C6 sugars, acetyl groups, and uronic acid. The smaller parts allow enzymes and chemicals to affect the mixture better and benefit the reaction. This process ultimately leads to the fermentation of sugars into ethanol. Then ethanol can be distilled to a wanted blend, so it can be used as a transportation fuel. (Shadangi, 2021)

There are also other routes for producing liquid, gaseous or solid biofuels that can be seen in Figure 1. Hydrolysis can be done through catalytic and biochemical conversion methods. Ethanol can be made from biochemical conversion and other liquid fuels can be obtained through catalytic conversion. Thermochemical conversion consists of gasification, pyrolysis or liquefication methods and produces syngas and bio-oils, which can then be refined into many different biofuels. (Shadangi, 2021)

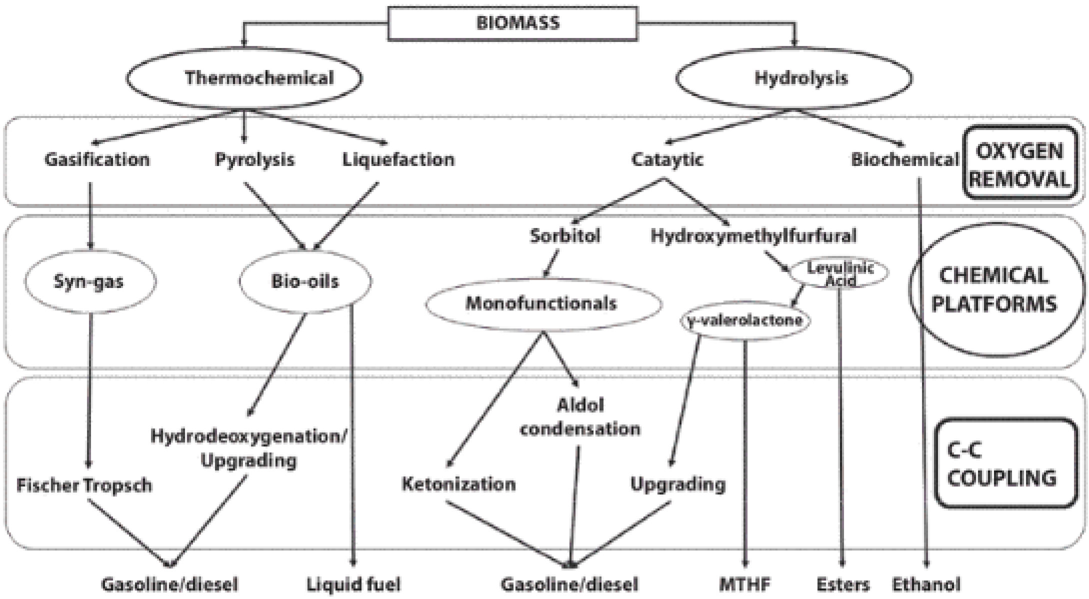

Figure 1. Biofuels production routes from biomass to liquid biofuels by thermochemical and hydrolysis. (Shadangi, 2021)

2.3.3 Biogas

Biogas can be produced from wastes, residues or energy crops via anaerobic digestion. In the absence of oxygen, microorganisms decompose the biomass, yielding methane and carbon dioxide. Biogas is a very versatile energy source and can be used in electricity generation, heat production and as transportational fuels. Biogas production is seen as one of the most energy efficient forms of bioenergy production. (Weiland, 2009)

Raw materials suitable for producing biogas can be any material that contains carbohydrates, protein, cellulose, and hemicellulose. However, materials like wood are not suitable due to their lignified structure. The type of feedstock used, and the digestion process employed at each location can impact the composition of the biogas produced. Raw materials can be evaluated based on their maximal yields, which refers to how much biogas can be produced from the substance, and theoretical methane contents. Table 4 presents the maximal yields and theoretical methane contents of different raw materials. (Weiland, 2009)

Table 4. Maximum yields and theoretical methane contents. (Weiland, 2009)

Substrate	Biogas (Nm^3/t TS)	Methane content %	Carbon dioxide %
Carbohydrates	790-800	50	50
Raw protein	700	70-71	29-30
Raw fat	1200-1250	67-68	32-33
Lignin	0	0	0

Biogas can be converted into heat and electricity by combustion in combined heat and power (CHP) plants. Biogas can also be upgraded and turned into transportation fuels. After biogas is formed, it contains impurities such as ammonia, nitrogen, and oxygen, which can impact negatively the performance of the fuel through corrosion and reduction of heating value. To get rid of these impurities, biogas must be cleaned and purified. After that fuels like hydrogen can be produced after reforming. Gasoline diesel and kerosene and be also produced via Fischer-Tropsch. From methanol, it is possible to refine gasoline from a process called Methanol to Gasoline (MTG). (Yang et al. 2014)

2.4 Conversion processes

As shown in Figure 1, biofuels can go through thermochemical or biochemical conversion processes. Thermal conversion processes include processes like pyrolysis and gasification and biochemical route includes fermentation, enzymatic reactions, and microbial conversion. It can be determined which route is better for a particular occasion based on the specific requirements and goals. If the goal is to maximize energy output, for example, electricity production, then the thermochemical route may be a better choice. However, the biochemical route offers many other benefits and is generally considered to be more cost-effective because it has lower energy requirements. (Pandey, 2011)

2.4.1 Fermentation

In fermentation, sugars are transformed into a mixture of yeasts. The mixture is then separated from the water with distillation and the result is bioethanol. Fermentation of starch is a bit more complex than simply fermenting glucose into ethanol. Starch needs to be enzymatically hydrolyzed first, then the liquid starch can be fermented into sugars with microorganisms. Coproduct is carbon dioxide. (Lin et al. 2006)

Hydrolysis of starch (Hoang et al. 2021):

$$(C_6H_{10}O_5)_n + n\,H_2O \rightarrow n\,C_6H_{12}O_6 \quad (1)$$

Fermentation can be divided into three methods, solid-state, liquid-state and high-gravity fermentation. Solid-state is often used when dealing with agricultural waste, it utilizes the development of microorganisms such as yeasts or bacteria on a solid body. Enzymatic hydrolysis of cellulose releases reducing sugars continuously, which are then saccharified and fermented. The result of this process is 2G bioethanol. (Betiku et al. 2023)

2.4.2 Gasification

Gasification is a thermochemical process for converting biomass into syngas, then it can be synthesized into synthetic fuel, as shown in Figure 2. The process involves exposing the components of the biomass to steam and controlled amounts of oxygen at high temperatures. The resulting syngas is primarily composed of carbon dioxide (CO2) and hydrogen. The ratio of air, steam, steam-oxygen, air-steam, or oxygen-enriched air can be adjusted depending on the desired outcome. However, before gasification, the biomass must be dried and pretreated to break down the lignocellulosic biomass into smaller components. (Ojeda et al. 2010)

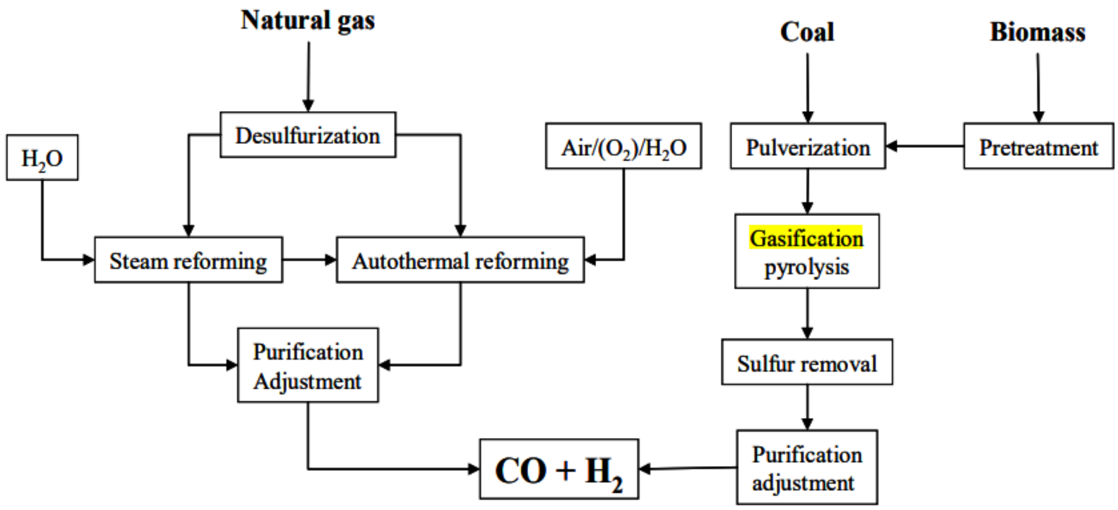

Figure 2. Routes for producing syngas. (Ojeda et al. 2010)

Syngas, which is produced through the steps shown in the figure above, often contain byproducts like tars. The cleaning process removes impurities and helps the catalyst keep working without being poisoned. Active metals can be used as catalysts to lower the operating temperature. However, removing tar remains one of the biggest challenges in syngas production. Tar removal can be achieved through scrubbing, catalytic reforming, and hot gas cleanup methods. (Ojeda et al. 2010)

2.4.3 Pyrolysis

Pyrolysis is a thermal decomposition reaction that occurs in the absence of oxygen. This process can lead to the production of liquid- and gas products. Depending on the conditions during the reaction, pyrolysis can be categorized into three types: conventional, fast, and flash. Conventional pyrolysis occurs at lower temperatures and heating speeds and has a longer residence time compared to fast (in the range of 0,5-10 seconds) and flash pyrolysis (<0,5 seconds). Solid, liquid, and gas products are produced during conventional pyrolysis. (Maitlis et al. 2013)

2.4.4 Fischer-Tropsch process

Fischer-Tropsch Process (FTP) was discovered in Germany in the 1920s. It is a term used for many industrial processes where syngas is converted to liquid hydrocarbons. There are a few different types of Fischer-Tropsch processes, for example BTL, XTL, WTL, and CTL, where the first letter stands for either ‘B’ for biomass, ‘X’ for coal, ‘W’ for waste, and ‘C’ for natural gas. In the future, capturing syngas from different biomass or organic waste will be more important as the world's fossil fuel reservoirs are emptying. Producing BTL fuels follows the same concept as in the liquid fuels made from coal or natural gas. The biomass is first gasified to syngas consisting of hydrogen and carbon monoxide in wanted ratios. Syngas is then converted to hydrocarbons and secondary products using a catalyst. A catalyst usually is a metal for example nickel, cobalt, or iron, depending on the wanted mixture. Low-temperature Fischer-Tropsch (LTFT) usually operates in the temperature range of 200-250 degrees and high-temperature Fischer-Tropsch (HTFT) at 320-375 degrees. (Maitlis et al. 2013)

The steps in producing Fischer-Tropsch fuels are:

1) Syngas formation
2) Fischer-Tropsch reaction
3) Refining

Chemical formulas for these reactions are:

1) $$nCH_n + O_2 \rightarrow \frac{1}{2}n\,H_2 + CO \tag{2}$$

2) $$2n\,H_2 + CO \rightarrow (CH_2)_n + H_2O \tag{3}$$

3) $$-(CH_2)_n \rightarrow \text{fuels, lubricants, etc.} \tag{4}$$

2.5 Applications

Biofuels can aid in improving energy security problems as well as provide solutions to the transportation sector. Biogas can provide heat and electricity when combusted in CHP plants. (Yang et al. 2014.) The transportation sector is one of the major contributors to greenhouse gas emissions (GHG). Therefore, it requires diverse options, including low carbon fuels (LCF), to tackle the issue. Even though internal combustion engine vehicles (ICEVs) have undergone significant improvements that made them more efficient, the source of energy is still a primary concern. (Benajes et al. 2024)

The choice of renewable fuel use for vehicles can be assessed by a few important criteria that are presented in Volvo's report on sustainable transport solutions. The factors to consider are presented in Figure 3 include the impact on the climate, energy efficiency, fuel costs, the cost of building new infrastructure, the potential of the fuel, and the necessary vehicle modifications needed to ensure optimal engine performance with the chosen fuel. (Volvogroup.com, 2015)

2.5.1 Road transportation

The global car industry is one of the most regulated sectors in the world. It includes safety measures, emission control, tax regulation, and environmental standards. With around 80 million cars produces annually, China manufactures the most with 25 million. In 2021, Toyota produced 4 million hybrid cars, with the Prius standing out as the most popular model. Although this is a small proportion compared to the world's annual production of 80 million cars, it shows great advancement in alternative technology vehicle production. For alternative fuel vehicles to make a positive impact on GHG emissions, they must be produced at a much higher rate. In long-distance heavy transport such as trucks or buses electrification or fuel cell use isn't optimal currently. Vehicles using batteries or fuel cells require proper energy storage systems and they increase the weight of the carrier. In short distance transport, such as city public transportation, hybrid or electric vehicles can be utilized better due to shorter distances travelled and the ability to use generated energy from braking. (Folkson et al. 2022)

Biofuels, such as bioethanol and biodiesel, are commonly used in road transportation as blends with gasoline and diesel. Ethanol is typically blended with gasoline in either 95E5 or 98E10, which contain 5%-10% ethanol and 90%-95% gasoline. Higher blends, such as E85, which contains 51%-85% ethanol, require modifications and can only be used in flex-fuel vehicles (FFVs). FFVs can adjust their engine performance based on the proportion of ethanol in the blend. (Corts, 2010.) FFVs are designed to withstand the corrosive nature of ethanol, especially the engines. However, the growth of FFVs still depends on several factors, such as the availability of refueling stations. Political factors like blending mandates and tax credits for producers can help to expand the market for FFVs and contribute to their growth. (Folkson et al. 2022)

The choice of renewable fuel use for vehicles can be assessed by a few important criteria that are presented in Volvo’s report on sustainable transport solutions. The renewable fuel assessment included biodiesel, synthetic diesel, dimethylether (DME), methanol, ethanol, biogas, biogas + biodiesel mixture, hydrogen + biogas mixture, electricity and hydrotreated vegetable oil (HVO). The factors to consider are presented in Figure 3. include the impact on the climate, energy efficiency, fuel costs, the cost of building new infrastructure, the potential of the fuel, and the necessary vehicle modifications needed to ensure optimal engine performance with the chosen fuel. Based on these criteria DME and methanol emerge as the most optimal choices. Still, the choice of fuel is not that simple as it includes this many different criteria. However, the chart is a good indicator which fuels showcase potential in road transport. (Volvogroup.com, 2015)

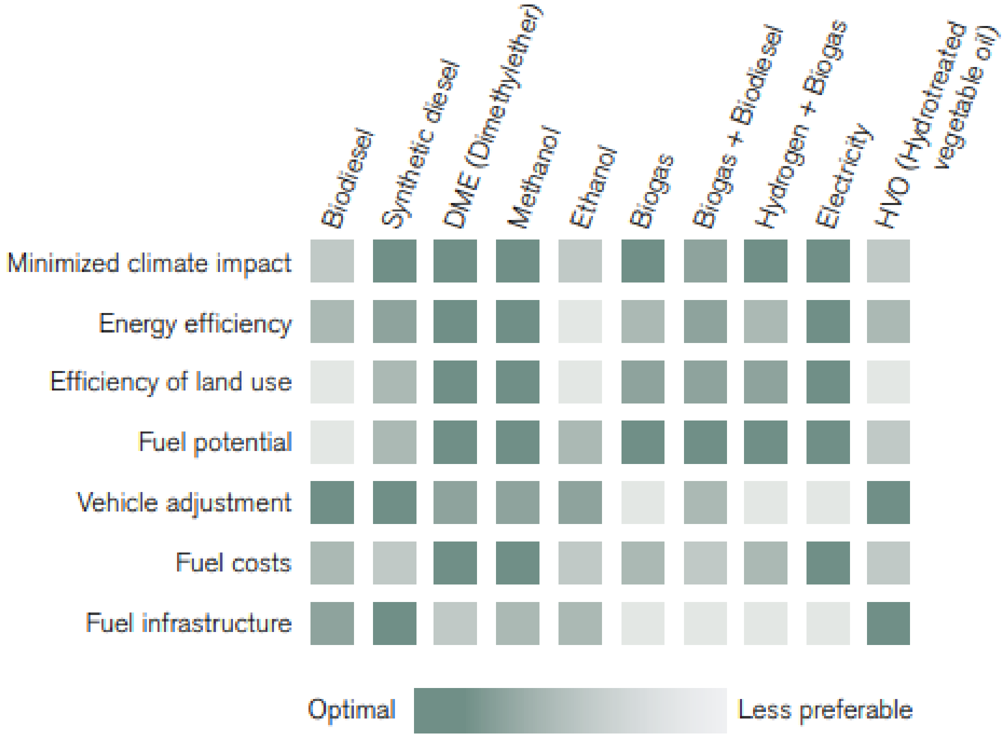

Figure 3. Renewable fuels: assessment of important criteria (Volvogroup.com, 2015)

2.5.2 Aviation sector

Sustainable aviation fuels (SAFs) provide a way for the aviation industry to reduce its greenhouse gas emissions. By mixing these fuels with traditional jet fuels, the aviation sector can transition to completely renewable energy while ensuring compatibility with current aircraft and infrastructure. SAFs can be produced from biomass sources through methods like Fischer-Tropsch synthesis and hydroprocessing. The most common SAF blends are SAF-5, SAF-10, and SAF-50, which contain 5%, 10%, or 50% SAF. (Morenike, 2023)

CORSIA, also known by “Carbon Offsetting and Reduction Scheme for International Aviation” aims to achieve carbon-neutral growth in international aviation from 2020 onwards. It means that the CO2 emissions shouldn’t rise in the future from the levels in 2020. To accomplish this objective, CORSIA has implemented two strategies. First is Carbon offsetting, and it utilizes “carbon credits” that are received from sustainable projects or initiatives that strive towards a reduction of GHG emissions. Additionally, CORSIA pushes airlines towards investing to cleaner technologies which can help improve fuel efficiency and reduce emissions. Figure 3 presents the classification of aviation fuels by the CORSIA. Lower Carbon Aviation Fuels (LCAF) are fossil fuel-based aviation fuels that produce fewer CO2 emissions compared to kerosene and meet the criteria established by CORSIA. (Chiaramonti et al. 2021)

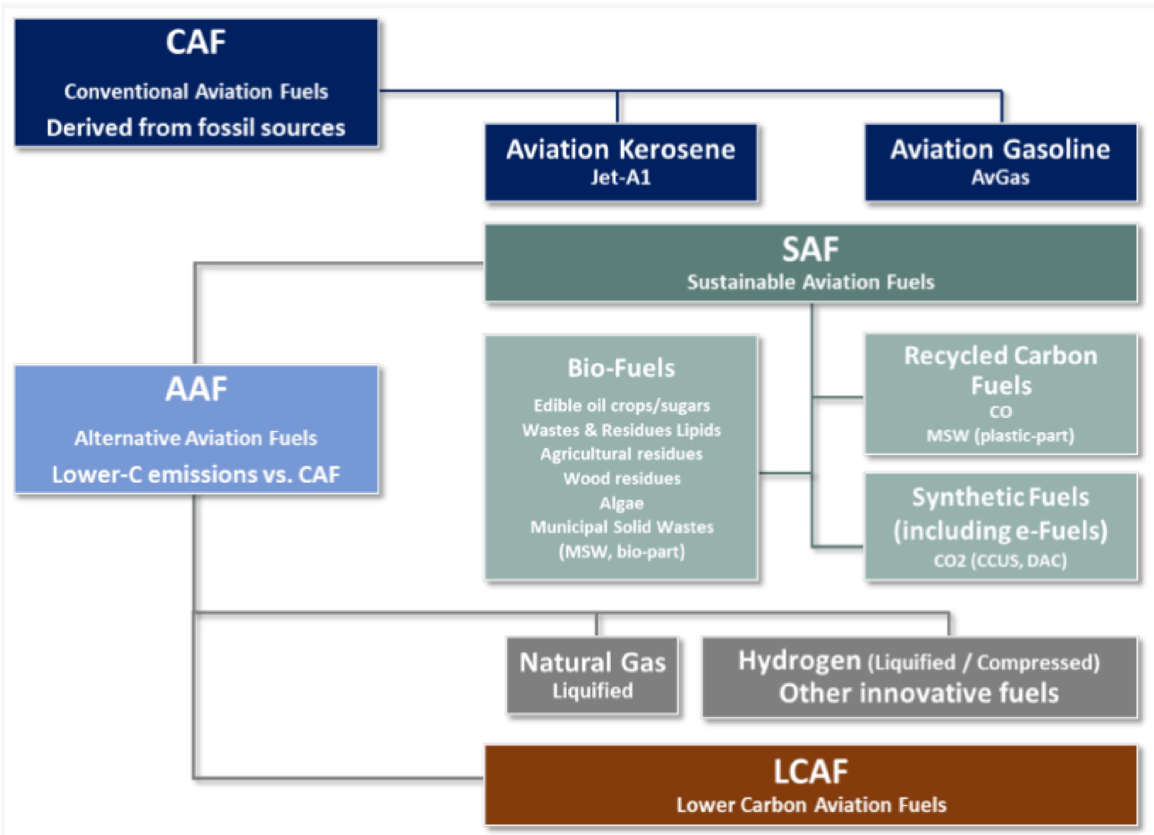

Figure 4. Aviation fuels classification. (Chiaramonti et al. 2021)

2.5.3 Marine transport

Marine diesel oil (MDO), marine gas oil (MGO) and heavy fuel oil (HFO) are still one of the most important fuels used in marine transport. Their downside is that they contribute heavily to air pollution. International Maritime Organization IMO has set a target for 2050 to reduce 50% of total GHC emissions annually. To reach this target, liquified natural gas (LNG) and methane are promising options. There needs to be a gradual phase-out process for conventional marine fuels and LNG and methane can serve as transitional fuels. However, they are not ideal long-term solutions as their ability to reduce CO2 emissions is limited. (Xing, H. et al. 2021)

Alternative carbon-free fuels for the future are ammonia and hydrogen. They offer flexibility as they can be produced from multiple feedstocks and via many production methods. Hydrogen, being the lightest element on earth, has a very low density by volume but high density by mass. It creates problems with storage and transportation as tanks of much larger volume would be needed. Ammonia is normally stored at -33 Celsius degrees in stainless steel tanks to prevent corrosion. If ammonia is leaked, the vapor can be dangerous for humans and the environment. Energy density is one of the most important qualities when considering a fuel for ships. Due to the poor density by volume, hydrogen and ammonia suit better for short sea or domestic shipping. In Figure 4 the energy densities and volumetric densities of different maritime fuel options are compared. (Xing et al. 2021)

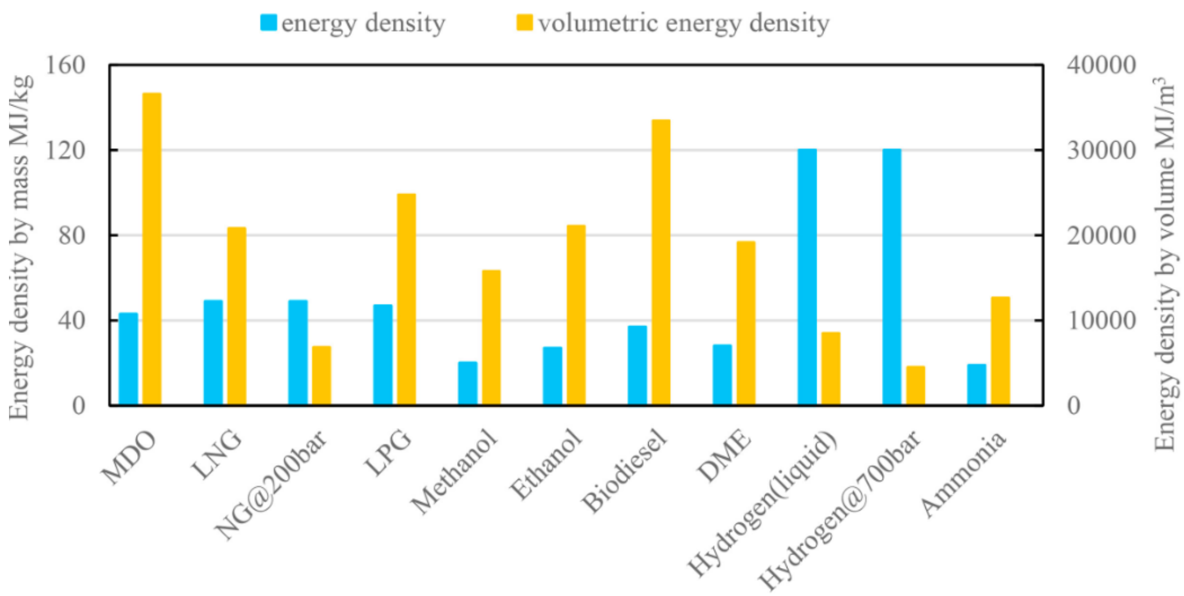

Figure 5. Comparison of energy densities for different marine fuels. (Xing et al. 2021)

Comparison between LNG and MGO, in terms of fuel consumption and price per year is summarized in Table 5. Although from the comparison LNG is more inexpensive to consume but the cost associated with the new infrastructure and carriers needed would increase the overall cost significantly. With ongoing R&D for LNG, it can become more cost effective overall compared to conventional marine fuels such as MGO and MDO.

Table 5. Annual fuel cost for the scenario of the economic assessment. (Yoo, 2017)

Fuel type	MGO	LNG
Oil fuel consumption per hour (1)	1137 kg/hr	930 kg/hr
Voyage time (2)	144h (6 days)	144h (6 days)
No. of voyages per year (3)	58	58
Annual oil fuel consumption (4) = (1) x (2) x (3)	9496 ton/yr	7767 ton/yr
Fuel price (2016) (5)	436 USD/ton	397 USD/ton
Annual fuel cost (6) = (4) x (5)	4.14 MUSD	3.08 MUSD

3 Future of biofuels

Energy security is a complex issue that involves various aspects such as geopolitical tensions, economic vulnerabilities, reliability, and environmental impact. Many countries rely heavily on imported fuel, and any disruption in the supply chain can cause significant problems. Rising energy costs can also affect negatively to economies and lead to potential international debt. Market fluctuations and unexpected rises in energy prices due to supply disruptions or changes in demand are challenges to energy security, as they can expose consumers and industries to price shocks. The electric power sector plays a vital role in energy security, and ensuring reliability and efficiency in power generation and distribution is crucial for maintaining stable energy supplies and mitigating risks. The transportation sector is known for its high energy consumption and pollution levels, and it brings challenges of its own. Therefore, promoting energy-efficient and sustainable transportation technologies such as biofuels and electric vehicles (EVs) is important for mitigating environmental impacts. (Tugcu et al. 2024)

3.1 Lignocellulosic biomass potential

In this section, we evaluate the biomass potential from agricultural residues in Europe. Figure 5 shows the geographical distribution of different agricultural-based biomass (energy crops, residues, manure) that can be utilized. Spain, France Poland, and Germany possess over 50% of the region's biomass supply. It is expected that bioenergy production from agricultural residues will increase significantly, reaching up to 25-30 megatons of oil equivalent (Mtoe) in 2030, which is a doubling of the use from 2012. When compared to forest-based biomass and organic waste (biowaste), agricultural residues have the highest potential for growth in the upcoming decades. (Directorate-General for Energy, 2017)

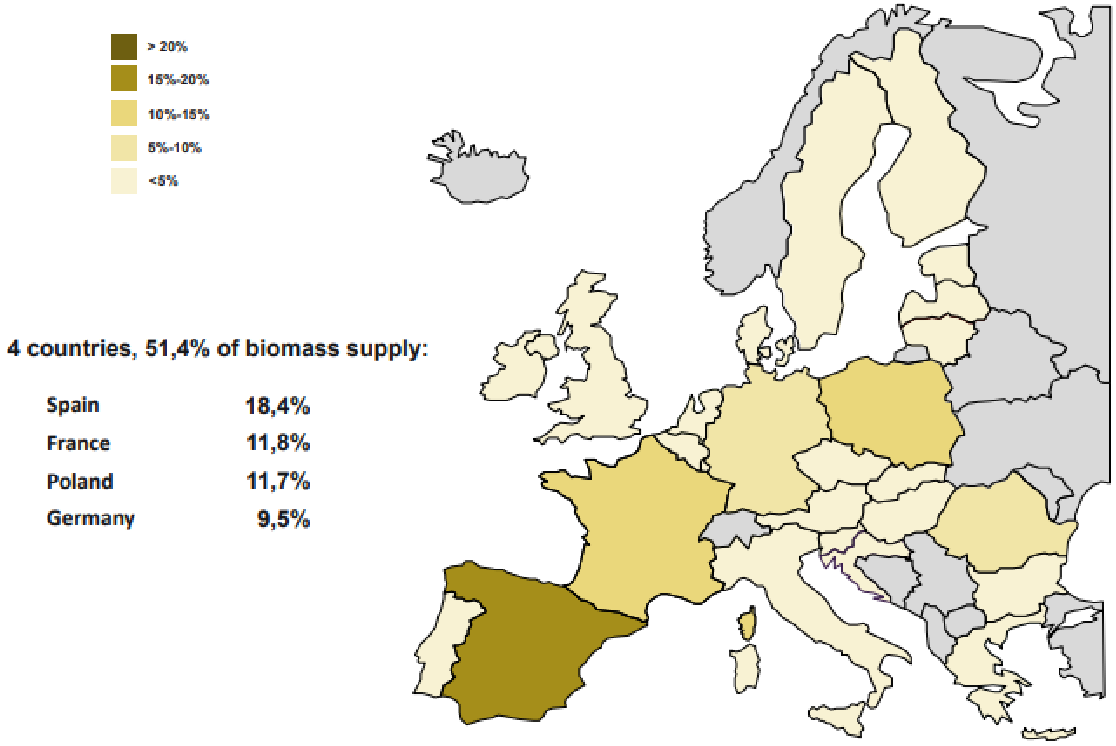

Figure 6. Agricultural biomass supply potential share (2030). (Directorate-General for Energy, 2017)

Dedicated energy crops are not food- or feed crops and are purely to produce bioenergy. Total supply potential in EU for energy crops is estimated to be 131 Mtoe in 2030, growing significantly from 39 Mtoe in 2010. Lignocellulosic crops, having the largest potential are expected to grow to 113 Mtoe in 2030 from only 11 Mtoe in 2010. However, the designated land area for energy crops is estimated to grow just 1 mega hectare (MHA) from 23 MHA in 2020 to 24Mha in 2030. Agricultural biogas is expected to grow from 15 Mtoe in 2010 to 40 Mtoe in 2030, making it the biggest source of energy supply. Agricultural biogas can be produced from animal manure, and it is the biggest source with 47%. (Directorate-General for Energy, 2017)

3.2 Policies

Renewable fuels like biofuels can be promoted through different market-pull and technology-based policies. Market-pull policies are designed to help the financial side of biofuels. They support the market penetration and the cost-competitiveness of biofuels. On the other hand, technology-push policies help in the research & development (R&D) of biofuels, especially in pilot stage and pre-commercialization. Biofuel blending mandates are the major market-pull policies for increasing renewable fuel use especially in the transportation sector. However, blending mandates have not been successful in some countries due to reasons such as lack of feedstock or their high prices, food security or concerns regarding sustainability. (Ebadian et al. 2020)

The US is one country with an established mandate which requires a certain volume of renewable fuels to be blended with conventional fuels and sold. The recent target was 36 billion gallons per year (BGY) by 2022. That consisted of 15 BGY of corn starch-based ethanol and 21 BGY of advanced cellulosic and biodiesel biofuels. Also, as a technological incentive, the US offers loan guarantee programs which intended to limit the financial risk of the construction of first-of-a-kind commercial facilities. As a result, the US has seen an increase in the production of biofuels, including a rise in biodiesel production from 215 million gallons in 2015 to 2,5 billion gallons in 2017. Numerous new projects with commercial advanced biofuels such as 2G ethanol, renewable diesel, and bio jet fuel have been established. While the most common policies for “Drop-in” advanced biofuels are technology push policies, Low Carbon Fuel Standard (LCFS) policies lean toward supporting more “ready” biofuels that are near commercialization. Drop-in biofuels are designed to fit into the same infrastructure and vehicle fleet as the current ones. (Ebadian et al. 2020)

Brazil has implemented various policies including both market pull and technology push, such as mandates, fuel excise tax reduction, tariffs on imported ethanol, fiscal incentives, and LCFS. LCFS policies have been implemented in some states in the US and its goal is decarbonizing the transport sector. One benefit LCFS offers is that it incentivizes efficiency and innovation in biofuel production while promoting the reduction the carbon intensity in all transport fuels. Many countries such as Germany and Denmark have adopted similar strategies also based on limiting GHG emissions. Their technological incentives include allowing funds for feedstock development and advanced biofuel production and their facilities. These incentives have been affected positively since the use of ethanol and biodiesel has risen 3% and 18% annually since 2008. They have also commercialized two cellulosic ethanol plants with one currently being in the demonstration stage. (Ebadian et al. 2020)

Governments around the world have been proposing fuel excise tax reductions to make biofuels more economically competitive with fossil fuels. For instance, the US offers biofuel blenders tax credits for bioethanol and biodiesel production. The goal for most countries is to remove or reduce these tax incentives as the price of biofuels becomes more competitive with fossil fuels. Australia has stated that they will remove the biodiesel excise tax once biodiesel achieves 50% of diesel price. (Ebadian et al. 2020)

Different sustainability policies have also been established around the world. Their goal is to advance the production of advanced biofuels that use non-edible feedstock such as agricultural- and municipal waste. A mandate EU RED II (The Renewable Energy Directive II) required a 50% reduction in GHG emissions in 2017 and 60% in 2018. Part of the policy prohibited biofuel feedstock farming in areas that store large amounts of CO2, such as forests and wetlands. Some countries have implemented carbon taxes which are considered to be market-pull policies. In Germany, the carbon tax is implemented through CO2 tax for passenger cars. Its goal is to internalize the external costs associated with GHG emissions. (Ebadian et al. 2020, Köppl et al. 2022).

All these mentioned policies have their proven strengths, but they also have limitations. Blending mandates have not been entirely successful in meeting GHG emission targets and in expanding to new markets. Excise tax reductions alone may not be a good enough driver for biofuels to become cost-competitive with fossil fuels, because the excise rates can vary a lot depending on the country. Still, countries that have seen the most growth in biofuel use have used a combination of market-pull and technology-push policies. Although the use of biofuels has increased significantly over the last two decades, still over 95% of the transport sector was fuelled by the petroleum industry in 2015. (Ebadian et al. 2020)

3.3 Key concerns

One of the primary reasons advanced biofuels are facing problems is the complexity of the conversion processes. The complexity ultimately leads to higher production costs and problems with large-scale commercialization. Another problem with large-scale commercialization is the competition of land area between biofuel production and food production. The land area available for agriculture is limited and isn't expected to grow significantly in the future, with less than 5% by 2050. Most of the growth happening in developing countries with 12% and decreasing by 8% in developed countries. With a growing population, the demand for food is also going to rise and that is why biofuel production mustn't compete with agriculture for resources such as land, water and fertilizers. (Popp et al. 2014)

As the global primary energy demand is seen to grow significantly in the future, from 2008 the projection was a rise was over 35%. With large-large bioenergy production in tropical and sub-tropical developing countries, deforestation is a serious concern. Deforestation is not only a threat to the ecosystem and biodiversity of the area but also by clearing land for designated energy crop land, it removes carbon sinks since forests are vital for the storage of CO_2. (Popp et al. 2014)

Large-scale biofuel production projects have the potential to lead to social implications such as displacement of indigenous communities as well as labour rights violations. Despite the success in implementing policies supporting the production of biofuels, the prices of petroleum and market uncertainty have led to investments decreasing from 2006 27 billion USD to under 2 billion USD in 2015 and just 250 million USD in 2016. In Figure 6 the investment cost associated with both conventional and advanced biofuels are presented. (Ebadian et al. 2020)

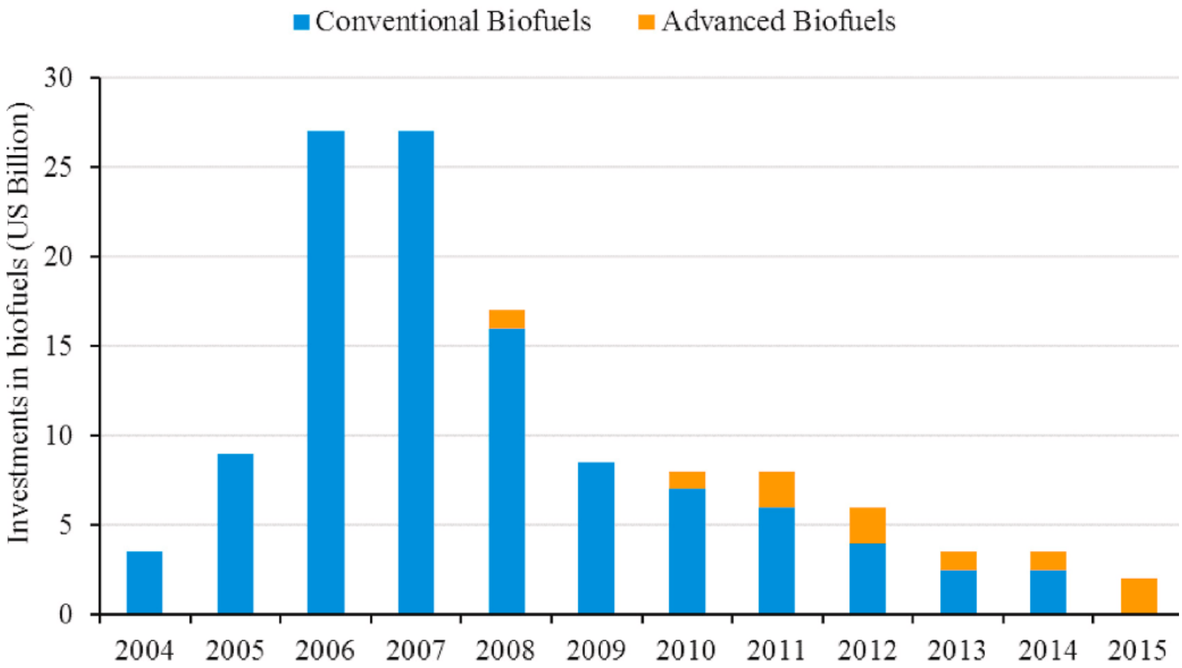

Figure 7. Global investment in advanced and conventional biofuels, 2004-2015. (Ebadian et al. 2020, Alberts et al. 2016, Hoefnagels et al. 2018)

Cellulosic ethanol plants are 2-3 times more expensive compared to corn-based ethanol plants. While cellulosic feedstock is cheaper and more available, capital costs are higher with cellulose-based ethanol plants. Combining different processes from the biochemical and thermochemical routes can help to cut costs. Logistical concerns with feedstock supply chains and financing continue to be the biggest issues with scaling up current production. (Popp et al. 2014)

3.4 Feedstock supply chains

Feedstock supply chains for lignocellulosic biomass offers many issues such as logistics of harvest, storage systems for both wet and dry biomass, preprocessing such as baling systems and pelletization and transportation. Additionally, they all require R&D investments to scale up the production of bioenergy and biofuels from lignocellulosic feedstock. When compared to other types of feedstocks such as grains or oilseeds, lignocellulosic feedstock has a lower bulk density which can increase transportation costs significantly. The transportation fraction describes the energy required for growing and transporting the feedstock to the biorefinery. For grains and oilseeds, it is 3-5% but for lignocellulosic feedstock it can range between 7-26%. Also, preprocessing is needed for the lignocellulosic feedstock before it can be transported to the biorefinery. Baling systems and pelletization are important preprocessing strategies and their goal is reducing the size of the biomass for more efficient transport. Despite the availability of numerous densification methods, the capacity required for lignocellulosic feedstock far exceeds that of grain and oilseed feedstock. Preprocessing can be conducted either on-site or in larger preprocessing facilities. (Richard, 2010).

Compatibility is an issue for several biofuels in fuel distribution. For example, ethanol cannot be stored or distributed through current pipelines. Some advanced biofuels that are yet to be commercialized, such as Fischer-Tropsch fuels and other gasoline/diesel equivalents claim they are compatible with existing pipelines. Some proposed business models for these logistical issues include independent local suppliers and large plantations where one company owns the land. This approach has encountered issues with employee rights and access to land. In regional or global commodity markets aggregators set clear specifications regarding the feedstock and the properties associated with it such as energy density, moisture levels, and particle size. (Richard, 2010).

3.5 EU customs

The EU has imposed tariffs for imported all ethanol products, especially for the cheaper ethanol that is imported from the US and Brazil. Brazil can produce ethanol cheaply due to the climate and efficient conversion methods. In the early 2000s, the EU set denatured ethanol tariffs at 0,102 €/l and for undenatured ethanol at 0,192 €/l. The goal of these tariffs was to protect European producers and in the case of an oversupply of ethanol in the market, it wouldn't lead to negative consequences for smaller markets like the EU. (Europa.eu, 2020, Junginger et al. 2014)

EU trade laws don't differentiate between the end use of ethanol, so thereby fuel ethanol is taxed the same way as would any ethanol product. Countries were able to avoid this tax by blending ethanol with gasoline at 12,5-20% and putting it under the classification "other chemical" and the tariff was reduced to 6,5% from 0,192€/l and about 63%. In 2020, the EU implemented a new customs code, (EU) 2020/1628 that targets imports of renewable ethanol fuel to the EU. The code indicated that taxing will be conducted for ethanol blends containing gasoline up to 30% at the rate of 102 €/cubic meter. (Europa.eu, 2020, Junginger et al. 2014)

4 Results

There are numerous conversion methods to produce 2G biofuels, for example the thermochemical and biochemical pathways. Each process offers its own benefits, which can make the choice for the most suitable process difficult. That offers flexibility but also means that the complexity increases the costs of the process. Challenges arise from preprocessing the biomass, logistics and production facilities.

There isn't a definitive solution for this problem since it includes multiple entities. The use of biofuels is currently heavily influenced by mandates, other policies and tariffs set by countries. Tariffs influence the use of biofuels in such a way that the majority of biofuel use in the world is domestic. Since many countries don't share the same policies and mandates regarding the blending rate, use and production of biofuels, it doesn't generate a level playing ground for the world and limits global trade.

Biofuels offer solutions to multiple fields including road transport, aviation, maritime transport, and electricity generation. The transportation sector is heavily regulated regarding safety, how much emissions are produced, and what environmental standards exist. The specific form of transport determines what fuel is most appropriate for certain applications. Long distance travel such as aviation and maritime transport are major producers of GHG emissions. These modes of transportation already have incentives and standards in place to reduce their carbon footprint. Alternative aviation fuels can play a crucial role in reducing emissions.

The transformation from the current fleet of vehicles, ships, and planes in the world into a new one would take time and that is why phasing out fossil fuels using biofuels as blends or as drop-in fuels will make the transition easier. Drop-in fuels include similar characteristics to conventional petroleum-based fuels and are designed to fit into the current fleet and infrastructure. Fishcer-Tropsch fuels can be drop-in fuels in some circumstances. They can be tailored for example to match aviation fuel characteristics and work in current airplanes.

Out of potential maritime fuels LNG and methane are potential short-term solutions since the costs associated with them are comparable to MDO and MDO and they produce significantly less GHG emissions. For long-distance applications electrification and fuel cells aren't the most optimal since they increase the potential load that the carrier can transport. Hydrogen for maritime transport is a promising option but its development is in such an early stage that is not currently financially or technologically a feasible option. For short-distance transport, hydrogen and electric-powered ships can be potential solutions in the future. For road transportation, various biofuels offer promising benefits. Bioethanol, biodiesel, biogas, and synthetic fuels like FT fuels all present potential options for road transport.

Based on important criteria, such as climate impact, fuel cost and energy efficiency, DME, synthetic diesel, and methanol provide the most all-around optimal fuel for road transport. Out of these options, DME and liquefied methane appear to be the most promising and viable for both long and medium-distance transport. Alternative fuels, such as ethanol or biodiesel, can be used in vehicles with minimal adjustments. However, they are less preferable options due to their greater climate impact and lower energy efficiency when compared to DME and methane. Electricity is a viable option for short-range applications but faces infrastructure challenges due to the need for accessible charging facilities.

Many industrial processes generate byproducts that are often burned for energy because they have no specific use. When processing lignocellulosic biomass, the first step is to remove the lignin, which is a challenging and energy-intensive process due to the tight structure of cellulose. However, instead of burning the lignin, it can be utilized by valorisation. This process involves chemical or biochemical conversion of lignin into smaller polymers that can be used to produce other valuable products, such as carbon fibres, bio-based polymers, or resins.

Currently, bioethanol is the most used biofuel, followed by biodiesel. Different climates around the world affect how biofuels can be used. For example, in colder climates, bioethanol has difficulties with cold starts in internal combustion engine vehicles (ICEVs) and it can also cause corrosivity. Flex-fuel vehicles (FFVs) have showed to be beneficial in Brazil and the US. FFVs can adjust their performance based on the blend of ethanol and gasoline on the fuel. Currently there could be potential for FFV use since the price of petroleum can fluctuate.

5 Conclusions

Biofuels serve as an important option for mitigating GHG emissions, reducing our dependency on fossil fuels, and promoting a way towards a renewable energy system. The use and production of 1G biofuels has been proven to be more cost-efficient, although it has raised concerns regarding food versus fuel debate as well as their environmental concerns such as loss of biodiversity and deforestation. 2G biofuels have the potential to solve these concerns while helping countries strengthen their energy security. However, they still face issues regarding their financial viability and complex processes.

This thesis reviews the challenges and opportunities to produce biofuels from agricultural waste. I reviewed the lignocellulosic biomass composition and its potential availability in Europe. Lignocellulosic biomass offers both challenges and benefits. It is widely available but the current infrastructure for its processing, storage, and transportation is inadequate for current and potential future needs. Preprocessing offers possibilities for future innovations. Currently baling and pelletization are popular solutions for the densification of biomass.

Despite policies supporting biofuels, like mandates, carbon taxes, and low carbon fuel standards, there are still concerns about the increasing demand for transport fuels. Many ongoing pilots and demonstrations provide development on advanced biofuels but there are challenges with preprocessing the biomass, logistics, and production facilities. They all require financial investment and supporting policies to boost production on a larger scale. A bigger change is dependent on multiple parties, such as private investors, energy producers, transportation companies, and fuel retailers. One solution for improving the usage and production of 2G biofuels includes countries unifying their blending mandates and sharing their policies to generate an even playing field. This could boost global trade and increase the availability of biofuels in different markets while promoting international cooperation. Also, it could help secure funding for R&D, as well as the production and distribution of biofuels.

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