Sustainable supply chains for maritime biofuels

Insights into the link between technology and feedstocks

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Disclaimer

This report is an interview study based on 14 interviews with experts in fields within a biofuel supply chain, from the sourcing of materials to the combustion. While interviewees granted their permission to publish statements cited in their name, none of the interviewees has read the entire report prior to the date of publishing. This study is part of the CLEAN SHIPPING research programme funded by NWO and was supervised by TU Delft (Biotechnology and Society, Faculty of Applied Sciences) and the Platform for Sustainable Biofuels.

Executive summary

Over the past two decades, major improvements were seen in greening electricity and heat production as well as passenger mobility. However, the heavy duty transport sector, i.e. trucks, shipping and aviation, has been identified as harder to abate due to their heavy dependence on cheap fossil fuels and due to their international operation, making them more challenging to regulate. In 2019, more than 40 % (i.e. 460 PJ) of the total Dutch transport energy consumption came from shipping [1] which renders it a priority for fast decarbonisation. As vessel lifetimes are a significant factor with about 20 – 25 years and investments are large, the sector's decarbonisation cannot wait until today's early-stage technologies have fully matured.

One option for fast decarbonisation is the use of *drop-in* biofuels. These fuels are fully compatible with their fossil counterpart, e.g. diesel, methanol or liquefied natural gas, and can thus make use of existing infrastructure and engine technology. Being based on plants that grow from sunlight and atmospheric carbon dioxide, they are fully renewable. Their combustion merely emits the atmospheric carbon again, and is thus contributing to the natural carbon cycle.

However, sustainable agricultural practices have to be ensured, as well as a lack of competition with other sectors such as food production. This study investigates the sustainability of future maritime biofuel supply chains by serving the following purposes:

1. To collate and share expert knowledge about conversion technologies, fuels and feedstocks for maritime biofuels
2. To conduct a two part analysis which on the one hand starts from market needs and on the other hand begins with the feedstocks, and determines where the two meet and match to ensure sustainable and responsible production
3. To develop a structured research approach to find suitable feedstocks for maritime biofuel production

Expert interviews about conversion technologies, fuels and feedstocks

In total, 14 interviews were conducted, 6 of which were dedicated experts in conversion and combustion technology, another 6 were experts in feedstock growth and sustainability aspects, and the remaining 2 were interdisciplinary. The technology interviews gave detailed insights into the fuels within the debate, including required feedstocks, fuel properties, production scale, and remaining time until commercialisation (if the fuel is not already commercial). One key finding was that the biofuels' social and environmental impacts are mostly determined by the underlying feedstock, as the conversion processes operate at high efficiencies and often energy self-sufficiently. Another key insight was that conversion technologies currently undergo a shift from specific (e.g. biochemical) towards non-specific (e.g. thermochemical) processes. Thermochemical processes are maturing fast and their products will enter the markets in the mid 2020s. This lays the foundation for a large scale lignocellulosic biomass demand.

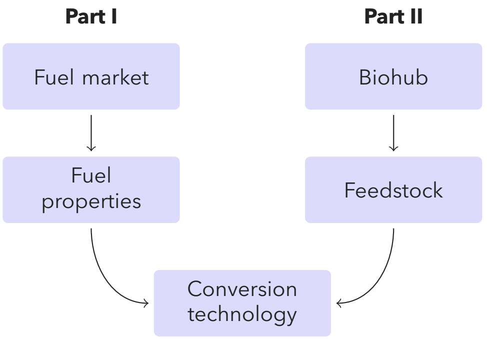
The feedstock and sustainability interviews yielded that the environmental and social impacts of a feedstock are highly contextual and thus cannot be generalised. Therefore, any framework needs to allow for contextual adjustments. Furthermore, sustainability criteria have already been worked out for most types of biomass and can already be independently assessed via certification schemes. One concern, however, was that neither certification schemes nor current bioenergy legislation consider social impacts of biomass growth appropriately. To tackle this, cooperation between biofuel producers and non-governmental organisations can be an effective measure.

Two part analysis

The supply chain for biofuels can be roughly divided into the biohub, the feedstock, the conversion technology, the fuel and the market. Between all these steps, logistics and transport is required. Breaking the analysis into two parts — one starting from the market needs and one starting from the biohub — allowed viewing the problem from different angles.

The market perspective values feasibility, efficiency and stability most. As demands for fuel bunkering are concentrated at port areas, the production scale of maritime fuels should be sufficiently high. Furthermore, the fuel should be affordable and contribute significantly to carbon reduction compliance. In short, its supply should be reliable and carbon abatement costs should be low.

The sustainable feedstock side values positive environmental and social impacts from the bioenergy project. A priority is replacing harmful practices with sustainable practices that provide ecosystem services as well as additional value to the farmer.



In their supply chain, the two views meet in the middle – the conversion technology. It becomes apparent how central the role of the conversion technology is for every bioenergy project: It needs to satisfy both the needs of the market and the needs of the biohub. Even though drastically different, these two views can harmonise with one another. The exact extent of their synergetic relationship, however, should be regarded in a time scale: Nowadays, especially liquefied biogas from anaerobic digestion is an option for biohubs, as its production traditionally valorises waste and it can be operated in small decentralised units. With a growing fleet of LNG-operating ships, liquefied biogas demands can be expected to grow in the future. This demand is further secured by the possibility to convert biogas into bio-methanol, which has superior combustion and storage properties over biogas. Methanol might therefore outcompete LNG as a fuel in shipping, but anaerobic digestion may potentially serve both demands.

In the short term (around 2025), thermochemical processes are expected to reach commercial scale and therefore generate a market pull on lignocellulosic biomass. Abandoned and degraded land can be restored by growing lignocellulosic biomass for energy. Furthermore, lignocellulosic waste can be fully valorised by those technologies. As of today, the conversion step from biomass to biocrude oil is favourably performed on a small scale. This allows for creating biohubs for pre-processing the biomass and transporting the biocrude with higher energy density to a centralised large-scale refinery for further upgrading. In order to accelerate the transition to renewable energy, lignocellulosic biomass production projects need to be realised as soon as possible. By ensuring the market availability of sustainable lignocellulosic biomass, a seamless entrance of thermochemical biocrude oil into the market can be achieved. It follows that cooperation between biomass producers and biomass converters is key for realising bioenergy projects.

Structured research approach to find suitable feedstocks for maritime biofuels

After identifying challenges and possible synergies in the sector of maritime biofuels, recommendations for a structured feedstock research are given based on literature, the expert interviews and the preceding analysis. Due to the innumerable variety of types of biomass, every feedstock assessment requires initial scoping. For this, it is recommended to first decide on a region for biomass production and on a market for biofuel sale. The region and the market help scoping as they provide the political context (laws, regulation, support, ambitions), as well as the socio-economic-environmental context. Furthermore, they determine the scale of production based on market volume and feedstock availability. Another advantage of using the region and market for scoping is that these factors are usually fixed depending on other parameters, such as pre-existing partnerships, experience, infrastructure or company agenda.

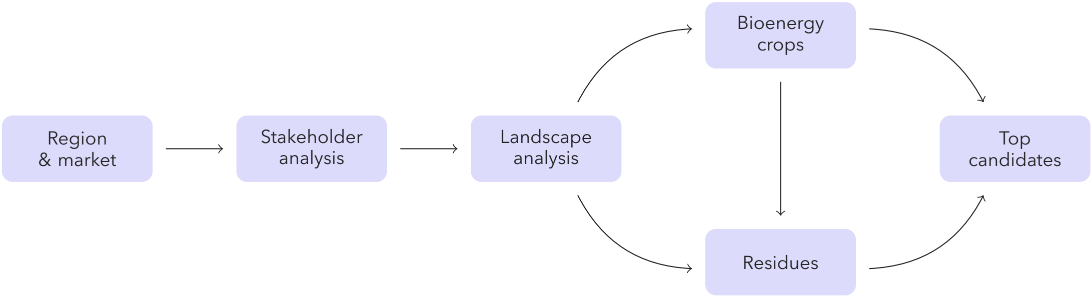
After the initial scoping, a regional stakeholder analysis is conducted. The aim of this analysis is to ensure that social impacts of bioenergy production are considered at an early stage. The stakeholder analysis identifies key players within the value chain, their roles and interests and room for improvement. This helps identifying value conflicts and diverging interests or agendas and address them in following parts of the project. Another part of this assessment is the power analysis, which determines decision-maker and land owner involvement. Established social indicators can be taken for a quantitative assessment, including food price indices or regional economic growth.

The stakeholder analysis is succeeded by a landscape analysis whose aim is to identify the *status quo* of land use and ecosystems in the area. Its focus lays in identifying unused biomass potentials that can arise from abandoned land, disposed residual biomass or non-optimally managed land. Following nutrient streams, such as nitrogen streams can be a helpful tool to identify unused potentials. It is hereby of importance to consider both the role that the biomass plays for humans (especially locals) as well as for nature. Only if the current unused biomass is potentially harmful for either humans or nature or if it does not play a role for either of them, the unused biomass potential may be harnessed. Apart from land uses, the current climate, ecosystems as well as pressures on biodiversity should be analysed.

The analysis then continues with harnessing unused potentials via either dedicated bioenergy crop growth or the use of identified residues. For dedicated feedstocks, the assessment should only continue if the crop is either indigenous to the area or proven to be non-invasive. It should relieve pressure on biodiversity, for instance by the choice of a type of biomass that is underrepresented in the region or one that forms synergies with fragile local ecosystems. In short, any feedstock should provide additional ecosystem services, and thereby serve a combined purpose for humans and nature.

For residues, the analysis proceeds in a similar manner. First, the roles for humans and nature are assessed. Residues may, for instance, fulfil a role for local energy production, nutrition or for maintaining soil fertility without these use-cases being sufficiently covered in the literature. If, and only if, a residue either serves no (ideal) purpose for humans or nature or is potentially harmful to one of them, it may be utilised for bioenergy production.

Lastly, the top bioenergy crops and residues are compared against one another based on their impacts per energy unit of biofuel. Since the impacts of a type of biomass are highly contextual, the environmental impact assessment should connect to existing work, most notably sustainability certification schemes. Amongst residues, the streams that occur closer to the biomass production within the supply chain should be prioritised, as they will generate more added value to the farmer. Even though the political playfield may determine methods for carbon accounting, neutral calculations should be performed in addition. This way, the actual environmental impacts allow for a fairer comparison and for a more stable business case irrespective of future modifications on double counting factors.



1 Introduction

Every year, the shipping industry requires about 12 Exajoules of energy, 85% of which come from deep sea transportation [2, 3]. This massive demand is met by an established infrastructure of heavy fuel oils (HFOs), the lowest-value product of fossil oil refinery. HFOs are the most contributing factor to the shipping sector's environmental impacts. Thus, alternative fuels are ultimately required to meaningfully reduce the shipping industry's impacts on the environment.

The United Nation's International Maritime Organization (IMO) applied pressure on the shipping sector by introducing strict sulphur regulations from the year 2020 onwards. In Emission Control Areas (ECAs), which can be found in the North Sea, the Baltic Sea and North American coastal regions, the sulphur content of the burnt fuel must not exceed 0.1 %, and in non-ECAs it must be below 0.5 % [2]. Compliance either requires a more refined fuel, which increases operating costs and life-cycle emissions, or the use of a SO_x scrubber [4]. In both cases, costs will increase and hence the margin between fossil and non-fossil fuels may tighten. Consequently, the sector gained momentum in searching for alternative fuels that comply with these new regulations.

Biofuels are an often mentioned alternative that have a low sulphur content, provide good to excellent compatibility with the current infrastructure and can achieve high volumetric energy densities [4]. Being based on biomass, biofuels contribute to atmospheric carbon fixation and release biogenic carbon when burned. For these reasons, IRENA described biofuels as 'the most relevant alternative for replacement or blending with fossil fuels in the transport sector' [5]. Nevertheless, the role of biofuels in the future transportation sector is heavily debated, as the sustainability of sourcing the required biomass in meaningful quantities faces much controversy [6]. The produced biofuel can only be as sustainable as its feedstock's agricultural practices. This does not only include environmental concerns, but also social integrity of all stakeholders into the value chain.

For the production of biofuels, there is a variety of technologies available at promising stages of development [7]. These technologies impose certain requirements on the feedstocks, such as water content or chemical composition. In order to assess the techno-economic, environmental and social benefits of one feedstock and technology over another, selection criteria are required that facilitate the decision process at an early stage of analysis. The project actively searches for common ground within the debate, and thereby finding a solution that most stakeholders agree with.

Challenges of implementing biofuels are the increased costs and the lack of experience, which is especially difficult because the shipping sector relies on thin margins and is highly cost competitive [8]. One approach to find sensible feedstock options is to start from the customer demands (i.e. the fuel price), work out suitable technologies and scales from there on and then identify feedstocks that match the selection criteria to contribute to environmentally friendly and socially just products. Another viewing angle tackles the production chain from the other side, thereby starting with environmentally friendly and socially just biomass production routes, then working out which technologies and scale make optimal use of this feedstock, and finally which prices can be obtained by such biofuel.

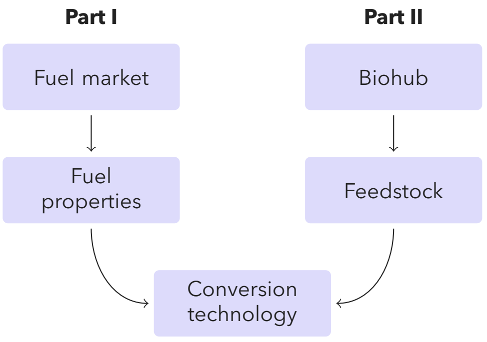


Figure 1: Two part analysis in this report starting from different angles in the supply chain. Part I focuses on the technology and market aspects, whereas Part II focuses on sustainability and feedstocks.

This project will employ each of these two viewing angles separately, and compare the obtained results. This allows for finding potential matches between the two approaches, i.e. biohub-compliant feedstocks that satisfy the market's needs.

To be more concrete about how to approach each of these two viewing angles, a set of questions need to be answered:

1. What is the current knowledge on biofuel options for shipping?
2. How are the biofuels produced, what is their conversion path?
3. How can the sustainability of feedstocks be ensured from an early stage?
4. What could a structured feedstock research procedure look like?

To answer these questions, knowledge from up-to-date literature is combined with semi-structured stakeholder interviews from experts in disciplines along the supply chain of biofuel production and use. Their expertises include sustainable agriculture, biomass conversion technology, marine fuel specification, combustion technology, supply chain optimisation, social development, feedstock sustainability and its certification. Their insights are used to collate knowledge and opinions on how to accelerate the bioenergy transition and which supply chains would be most beneficial for a given conversion technology. *Most beneficial* is hereby to be understood from a biohub perspective (see Sec. 5). Finally, the insights of the interviews and literature lead to a specific feedstock selection approach that aims to operationalise and facilitate the multidimensional choice around feedstock selection.

2 Background

With the IMO's initial decarbonisation strategy published in 2018 [9], the maritime sector gained a mutual GHG reduction ambition for the first time. Many feasibility studies on alternative fuel or technology comparisons followed during that time as a result of the sector's newly-gained momentum.

In the same year, the overall share of non-fossil fuels in the shipping sector was still negligible (Fig. 2). Of the 44 million tonnes in fuel demand monitored by EU-MRV, slightly more than 70 % are met by HFO [10], which is the lowest value product of fossil oil refineries. Being a residual, it is one of the cheapest fossil fuels and available in large quantities. As most sea-going ships are equipped with particularly large, slow-running and robust 2-stroke diesel engines that can handle low quality fuels [4], today's maritime infrastructure and engines are predominantly adapted to HFO. Another 20 % of the EU-MRV monitored fleet's fuel demand is lighter distillate oils such as marine diesel oil (MDO) or marine gasoline oil (MGO). About 3 % are attributed to liquefied natural gas (LNG), which comprises LNG carriers, but also increasingly newbuilds of other types [7, 11]. A 2017 ICCT study found comparable values for global shipping consumption in 2015, namely 72 % residuals (HFO), 26 % distillates (MDO, MGO) and 2 % LNG [12].

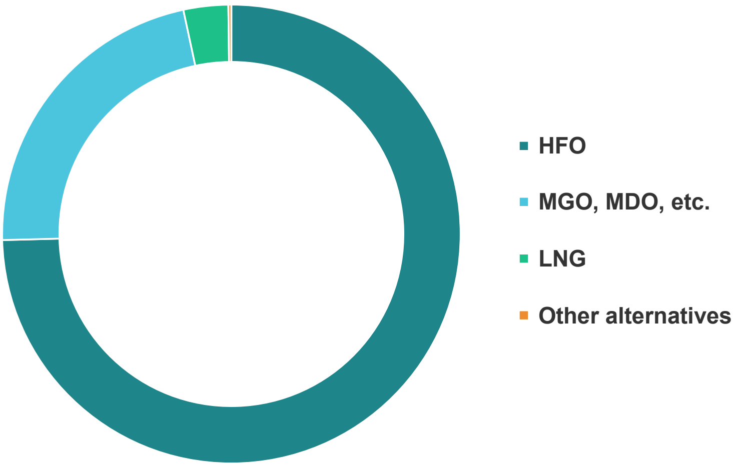


Figure 2: Fuel mix of the EU-MRV monitored fleet in 2018 [13].

The heavy dependence on HFO also becomes apparent when looking at the share of vessels of the monitored fleet: 94 % of the ships within the EU-MRV fleet burn HFO, whereas the remaining 6 % explicitly do not burn it [10]. The difference in these numbers to the formerly mentioned fuel demand can be explained by strict emission regulations in port areas and Emission Control Areas (ECAs) [2], in which most HFO-consuming ships temporarily switch to (low sulphur) distillate oils (MDO, MGO) [7, 14].

Worldwide maritime fossil fuel consumption has been estimated to 330 million tons per year [4], corresponding to approximately 1.1 $GtCO_2e/yr$ [14, 15]. Consequently, if the international shipping sector were a country, it would be the 6th largest global CO_2 emitter, exceeding the emissions of Brazil and Germany [15]. With recent global GHG emission estimates for the year 2019 [16], shipping emissions from ideal fuel combustion would roughly constitute 1.9 % of global GHG emissions. Taking inefficiencies and further life-cycle emissions in shipping into account, the contribution to global GHG emissions is often calculated to range between 2 – 3 % [3, 4, 12, 14]. If the shipping sector continues to not sufficiently address climate urgency, its contribution to global GHG emissions may rise to 17 % until 2050, taking GHG reductions of other sectors into account [17]. The maritime sector's large contributions to climate change reinforce the urgency to act upon reducing its share.

In 2013, a study found that efficiency measures that are technically available by 2020 will allow for decreasing an average ship's GHG emissions by up to 33 % [18], most of which (22 %) improve economics as well. It follows that to reach the IMO's target of 50 % GHG reductions by 2050, another 17 % GHG reduction is required from the choice of fuels. This translates to an immense renewable fuel demand ranging from about 70 to 120 million tonnes per year[1].

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[1] based on GHG emissions savings between 45 and 80 % on a mass basis

Based on their raw materials, renewable fuels can be divided into synthetic fuels and biofuels. Synthetic fuels are produced *de novo* from monomers such as CO_2 and water, and then catalytically elongated. If electricity is used to drive the reaction, this route is called *Power-to-X* or, specifically in case of a liquid fuel, *Power-to-Liquid* (PtL). Biofuels are energy carriers produced from biogenic origin, such as vegetable oils, sugars or biomass. In analogy to PtL, liquid biofuel production routes are named *Bio-to-Liquid* (BtL).

A scale-up of synthetic technologies is currently hindered by their low technology readiness level (TRL), high energy demands and the low availability of renewable electricity [19], which is consequently competing with other sectors. Only in some case, for instance for e-methanol production in Iceland, these hurdles can be overcome where renewable geothermal energy is abundant [19]. Biofuels, on the other hand, offer a potential short-term solution to rapid decarbonisation due to their high TRL, relatively limited cost and compatibility with fuel infrastructure and engine technology, often referred to as *drop-in* [20]. Due to these reasons, the IMO's fourth GHG study estimated synthetic fuel price projections for 2050 twice as high as their biological counterpart [14] and other studies comparing the two groups of fuels found biofuels to become a more viable solution than synthetic fuels in commercial shipping [21, 22].

Generally speaking, *drop-in* fuels are the most convenient option for large scale decarbonising in the short to mid term [4], as they are functionally equivalent to their petroleum counterparts and thus require little to no modifications to the established fuelling, bunkering and ship infrastructure and engines [4]. Some of the fuels mentioned in the following chapter are drop-in fuels for HFO and diesel, making them particularly interesting for the short to mid term.

3 Biofuels and their production routes

In the debate around decarbonising the shipping sector, a multitude of alternative energy carriers is included. The discussion often revolves around ammonia (NH_3), hydrogen (H_2), natural gas (mostly CH_4) and methanol (CH_3OH). When discussing short-term biofuels specifically, other alternatives are liquefied biogas (LBG), bio-ethanol and biomethanol, dimethylester (DME), straight vegetable oil (SVO, also known as PPO/PVO), fatty acid methyl esters (FAME, also known as biodiesel), hydrogenated vegetable oil (HVO, also known as HEFA), Fischer-Tropsch (FT) renewable diesel, hydrothermal liquefaction (HTL) oil, upgraded pyrolysis oil (UPO) and lignin diesel oil [4, 7]. An overview of the considered fuels and their production technologies is given in Tab. 1.

Table 1: Overview of renewable energy carriers commonly mentioned in the debate around alternative fuels for the shipping sector. The check mark signifies which options are of biogenic origin, and thus are considered biofuels.

Renewable carrier	Production technology	Biogenic
LBG / LNG	Anaerobic digestion	✓
	Gasification & cat. reaction (Sabatier process)	✓
	Electrolysis	
Hydrogen	Electrochemical water-splitting	
Ammonia	Haber-Bosch process with ren. hydrogen	
	Ammonia electrolysis with wastewater	
Ethanol	Fermentation from sugars	✓
	Fermentation from lignocellulosic waste	✓
Methanol	Anaerobic production of methane & dehydration	✓
	Gasification from solid biomass	✓
	Electrolysis of water + CO_2	
DME	Gasification	✓
	Dehydration of bio-methanol	✓
SVO	Extraction from plants	✓
FAME	Transesterification of vegetable oils	✓
HVO	Hydrogenation of vegetable oils	✓
Renewable diesel	FT, HTL, pyrolysis, HVO	✓
Lignin diesel oil	Solvolysis	✓
Electricity	Solar or wind	

This report focusses on biofuels, thus exclusively the above-mentioned energy carriers of biogenic origin are further considered. The following information is based on up-to-date literature and eight interviews with experts in the field of biofuel production. It forms part 1 of the analysis (see Fig. 1), and answers the question on the current knowledge on biofuels and their conversion pathways.

As mentioned before, the maturity of biofuel production processes renders them particularly interesting. A common qualitative indicator of technological maturity is the Technology Readiness Level (TRL) developed by NASA in 1989 [23]. The TRLs range from 1 to 9, where 1 denotes the observation of a phenomenon and 9 denotes the full commercial maturity of a technology. In short, TRL 1 – 3 are different levels of fundamental research, TRL 4 – 5 are research prototypes, TRL 6 – 7 are demonstrations in pre-industrial scale and TRL 8 – 9 are processes ready for commercialisation or already commercially available [7]. The TRL of each biofuel production technology is either cited from recent literature or estimated based on literature and the expert interviews.

It is important to note that GHG emission savings are often cited directly from the European Renewable Energy Directive [4, 7], even though it uses a fossil fuel comparator of 94 g CO_2/MJ that is targeted at road transport [24]. For maritime transport, it is more appropriate to adjust the fossil fuel comparator to HFO and ultra-low sulphur diesel (ULSMDO), whose well-to-propeller GHG emissions are 87 g CO_2/MJ [25–27]. Therefore, the GHG emissions savings mentioned in this report are slightly below the values mentioned elsewhere.

A common ground amongst the interviewees and also the literature can be found in acknowledging that there is no 'silver bullet' solution (see e.g. [2, 15, 20]). Decarbonisation options will remain context-specific and the choice will depend on detailed social, economic, environmental and technical implications of the considered fuels [20]. Therefore, most experts expect a diverse mix of alternative fuels and energy in the future. The goal of this report is hence not to determine a winner among the fuel options, but to compare them and to comment on their compatibility with the biohub concept (see Sec. 5).

3.1 Mechanical and chemical production routes

Mechanical and chemical extraction of oils from plant material is a traditional method for the production of vegetable oils, including SVO. Over the years, chemical conversions of vegetable or animal fats were added for products that are targeted at the fuel sector. These fuels comprise FAME and HVO. Due to their commercial availability, these fuels all have a TRL of 9. SVO, FAME and HVO together made up 80 % of all biofuels consumed in 2019 within EU-28 [28].

3.1.1 Straight vegetable oils

Straight vegetable oils (SVO) are plant-based oils that are used as a fuel without further upgrading. They are also called pure plant oils (PPO) or pure vegetable oils (PVO). They have a lower heating value (LHV) of 37 MJ/kg and a higher heating value (HHV) of 40 MJ/kg, which is about 5 % lower than that of HFO. SVO is a drop-in replacement for HFO in low-speed deep sea engines. Modifications in the fuel delivery system preheat SVO to address issues that would otherwise arise from its relatively high viscosity. Its high boiling point, however, poses a potential risk of engine damage [4].

Considering the feedstock, only oily crops are suitable for SVO production. Typical feedstocks are rapeseed, sunflower, soybean or oil palm. As residues, used cooking oils (UCO) are a suitable option [24].

SVO (UCO) costs around 16.2 – 20.8 EUR/GJ [29]. The GHG emissions savings are around 60 % from dedicated bioenergy crops, and 98 % from UCO [24].

3.1.2 Fatty acid methyl esters

Fatty acid methyl esters (FAME) are commercially available biofuels obtained via transesterification of vegetable oils or animal fats. They are also known as biodiesel due to their blendability with fossil diesel and their suitability for diesel engines. High blends of up to 40 % (B40) have been demonstrated to work in shipping, and theoretically the use of B100 is also possible [30]. B20 blends are commonly used and guaranteed to work as a drop-in replacement by ship engine manufacturers [4]. FAME has a LHV of 38 MJ/kg and a HHV of 40 MJ/kg [4].

Although concerns about its oxidation stability can be found in the literature [4], 'most claims about degradation or hygroscopy can be traced back to poor housekeeping or tank maintenance' according to Michael Fiedler-Panajotopoulos from Renewable Energy Group International (REGI). 'Such practices would have led to similar problems in conventional petroleum-based fuels', he adds. A recent study of the U.S. Department of Energy's National Renewable Energy Laboratory indicated that marketed B20 has a minimum shelf life of at least one year, with almost half the samples having a predicted shelf life of over 3 years. The study furthermore concluded that simple monitoring and well-timed re-additisation with BHT (a common stability additive) can extend the shelf life of B20 to over 4 years [31].

FAME rely on oils and fats, and therefore require oily crops or residues for their production. Nowadays, typical feedstocks are rapeseed, sunflower, soy bean and oil palm [24] as dedicated crops, and UCO as residues. To the common concern about the limited availability of oily crops and residues, Michael Fiedler-Panajotopoulos answers 'We're a piece to a puzzle. Near-term decarbonisation is desperately needed to meet the ambitions of the Paris Agreement, and biodiesel can provide just that while other innovative technologies continue to evolve and mature.' Furthermore, UCO capacity shows no signs of peaking yet, as the production of FAME and HVO continues to grow [28].

With rapeseed, GHG reductions of 54 % are achieved [7, 30], while UCO achieves around 87 % [24, 30]. Prices for UCO-based FAME range between 21.5 and 26.3 EUR/GJ [29].

3.1.3 Hydrogenated vegetable oils

Hydrogenated vegetable oils (HVO), also known as hydroprocessed esters and fatty acids (HEFA) or renewable diesel are vegetable oils or animal fats that have undergone severe hydrotreatment to crack the molecule [30]. Similar to biodiesel, they are commercially available and have a LHV of 43 and a HHV of 47

MJ/kg. However, due to their lower density, their energy density is lower than that of FAME. Despite its name as 'renewable diesel', it shares more characteristics with MGO than with MDO, and meets ISO 8217 specifications in its pure form [7].

'When not operated in very cold climates, biodiesel is the winner in commercial shipping due to lower cost and since high quality fuels are not required', Michael Fiedler-Panajotopoulos explains [30]. 'Ship engines are much more robust than car engines, and the advantages of HVO (prolonged stability, higher fuel quality and better cold flow properties) do not justify the higher price'. The higher fuel quality also makes HVO more attractive to target road and aviation transport, where the price difference to other fuels is lower and thus more competitive [7].

According to the EurObserv'er report, European production scale of HVO is currently at over 3 million tons/yr with an average plant capacity of 380 ktons/yr. By 2024, European production is projected to exceed 5.2 million tons/yr, with an average plant capacity of about 440 ktons/yr [28].

Similar to FAME, HVO requires oily feedstocks or residues for its production. Mostly, this comprises rapeseed, sunflower, soybean and oil palm, as well as UCO [24]. When using waste oils, GHG savings can be as high as 86 %. From dedicated crops, the GHG savings are up to 55 % [24]. Based on Neste's Q3 market report [32], an S&P Global Platts market analysis [33] as well as the upper range of prices reported by E4tech [7], prices can be estimated to be around 24.2 – 32.6 EUR/GJ.

3.2 Biochemical production routes

Biochemical reactions are reactions that are realised by a biocatalyst, such as microbial organisms, microbial communities or enzymes. Generally, they are highly specific to their feedstock and occur during mild conditions, i.e. around room temperature, atmospheric pressure and neutral pH. The most viable biochemically-produced fuels for the maritime sector are liquefied biogas (LBG) and ethanol.

3.2.1 Liquefied biogas

Liquefied biogas (LBG) may be regarded as the bio-alternative to LNG, which is why it is sometimes referred to as bio-LNG. It is liquefied biomethane, thus has a lower heating value of 48 and a higher heating value of 55 MJ/kg [4].

LBG can either be produced via a biochemical process called anaerobic digestion or via a thermochemical gasification of biomass (see Sec. 3.3.1). In the process of anaerobic digestion, biomass is hydrolysed into its biochemical components cellulose, hemicellulose and lignin under the absence of oxygen. The polysaccharides cellulose and hemicellulose are then further catabolysed by acidogenic and acetogenic bacteria into volatile fatty acids (VFAs), hydrogen and carbon dioxide. These can be metabolised by methanogenic bacteria to biomethane [34]. The resulting gas mix is called biogas. After the removal of CO_2 and trace gases, LBG is obtained by lowering the temperature to below methane's boiling point.

While anaerobic digestion to biogas has been commercially available since many years, as well as the upgrading of biogas to biomethane (TRL 9) [4, 35], commercial scale plants that include the liquefaction to LBG are still rare and just opening at the time of writing this report [36, 37]. However, the liquefaction of biomethane does barely differ technically from the liquefaction of natural gas, the latter of which is readily available, too. Therefore, the lack of LBG plants may be explained by a lack of market demand. Whereas biomethane is ready for supply into the gas grid, for electricity and heat production and fuel use as compressed biogas (CGB or bio-CNG), the benefits of LBG lay in special use cases, as fuel in heavy-duty transport and shipping [35].

Anaerobic digestion is suitable for the valorisation of most types of biomass, including wet lignocellulosic biomass. It supports wastewater treatment by valorising activated sludge and can furthermore valorise manure and the organic fraction of municipal solid waste [35]. However, biomass with a high lignin content such as forest residues or other sorts of woody biomass will result in low yields, as the microbial communities are not able to quickly convert lignin. Additionally, the feedstock's C/N ratio should be high to avoid methanogenesis inhibition by ammonia formation [38], which impedes the usage of algae or protein-rich feedstocks.

LBG prices were estimated to range between 15.1 and 44.2 EUR/GJ[2] [7] and have been described as expensive elsewhere [40], suggesting they are more towards the upper side of the given range. GHG savings range between 72 and 82 % [7].

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[2] After applying a 30 % heuristic increase from production cost to minimum selling price [39]

3.2.2 Bioethanol

Ethanol is the second shortest-chain alcohol after methanol and has a LHV of 27 MJ/kg and a HHV of 30 MJ/kg. Brazil is most known for its large-scale ethanol biorefineries from sugar cane, but large-scale ethanol fermenters can be found all over the world. In Europe, about 18 % of biofuels consumed in 2019 was bioethanol [28], typically as an E5 or E10 blend with petrol in road transport.

Bioethanol is produced via fermentation, i.e. the anaerobic conversion of sugars or acids by microorganisms. Baker's yeast, or scientifically called *Saccharomyces cerevisiae*, shows hyperproductive strains that are conventionally employed in industrial ethanol production.

According to EurObserv'er, the European production of cellulosic ('advanced') ethanol amounts to about 54.5 ktons/yr, of which 40 ktons are produced in one facility (Versalis in Crescentino, Italy). Many equally sized production plants will start operation soon, extending the European production scale to about 475 ktons/yr by the mid 2020s. The average production plant scale will then be around 30 ktons/yr [28]. This indicates that cellulosic ethanol is about to enter TRL 8.

As a feedstock, streams of high carbohydrate content are favourable. For dedicated bioenergy crops, this mostly comprises sugary or starchy crops such as sugar beet, sugarcane, sweet sorghum, corn or other cereals [24]. Residual streams may be wastewater of juice or syrup production or wet coffee waste [41, 42]. Another method to obtain simple sugars from biomass is via hydrolysis of cellulose and hemicellulose which allows for the valorisation of most types of biomass. This leaves the lignin fraction of biomass behind and, consequently, makes woody biomass rather uninteresting for ethanol production.

According to Hennie Zirkzee from Biondoil, the high price of ethanol is most likely a cut-off criterion for use in shipping [43]. 'I am not aware of any demonstrations of ships running on ethanol', so Hennie Zirkzee. 'When opting for alcohols, methanol will be cheaper and hence more interesting for the maritime sector.' In order to cut down costs, Hennie Zirkzee stresses the importance of valorising each by-product as much as possible. 'Simply burning lignin to cover the plant's energy requirements is the lowest-value application, yet many second generation biorefineries choose to do so.' In the future, lignin may be a useful platform chemical for the production of sustainable coatings, composite materials or asphalt, which can be sold at a higher price [43]. Lignin can also be converted together with ethanol into a more diesel-like fuel [44], as explained in Sec. 3.3.5 below.

Nevertheless, it should be noted that bioethanol is available in large quantities. Its supply potential is expected to be able to displace the whole fossil fuels volume required in the maritime sector [4]. Currently, ethanol-consuming ships would require retrofits similar to methanol-consuming ships [45], but there are developments towards multi-fuel engines (LGI engines) that can combust oil, gas, and alcohols in a diesel cycle [4, 40]. These developments may incentivise the increased use of ethanol in shipping.

GHG savings range broadly from 22 to 78 % from dedicated carbohydrate crops and are in the order of 84 % for cellulosic ('advanced') ethanol from wheat straw [24]. This shows that under the right circumstances, conventional ethanol from dedicated carbohydrate crops can yield high GHG emissions savings that are comparable to cellulosic ethanol production. The 78 % GHG reductions refer to the case 'sugar beet ethanol with biogas from slop, natural gas as process fuel in CHP plant' as calculated in the Renewable Energy Directive II [24].

Conventional ethanol prices from dedicated crops have been estimated to 19 – 22 EUR/GJ [7], whereas prices for advanced ethanol from residues have been estimated to 31.1 – 37.7 EUR/GJ [7] [3].

3.3 Thermochemical production routes

Thermochemical processes are production routes that rely on decomposition effects that occur by applying heat and pressure. They thereby mimic natural processes that produce fossil oils and gas from biomass over millions of years, but accelerate them to a timescale of seconds or minutes.

The major components of biomass — cellulose, hemicellulose and lignin — decompose and depolymerise into oligomers. Depending on the process, either the oligomers further decompose into smaller molecules or they repolymerise into long hydrocarbon or fatty acid chains.

3.3.1 Bio-synthetic natural gas

Despite creating the same product, biogas that is produced thermochemically is called bio-synthetic natural gas (bio-SNG) instead of LBG or bio-LNG [35]. Nevertheless, physico-chemical properties including

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[3] After applying a 30 % heuristic increase from production cost to minimum selling price [39]

heating values (mentioned in Sec. 3.2.1) remain the same for all these different definitions, as the product is chemically equivalent (i.e. mostly methane, CH_4).

The underlying process is a gasification of solid biomass to syngas [4], a mixture of CO, H_2 and CO_2. Gasification takes place at around 900 °C, under high pressure and in absence of oxygen [4]. The syngas is then catalytically converted into methane in the Sabatier process. This requires high temperatures between 300 and 400 °C as well as elevated pressure [4].

Already in 2015, about 40 % of Finland's and 10 % of Spain's biogas production were thermochemical [35]. None of the other EU-28 Member States, however, reported thermochemical biogas production to Eurostat in 2015 [35]. This indicates that the TRL for bio-SNG production is 9 in Finland and Spain, whereas it is significantly lower elsewhere. Based on recent industry insights given to the Platform Sustainable Biofuels, the TRL of bio-SNG is around 7 in the Netherlands. This is in line with the TRL mentioned elsewhere [7].

3.3.2 Biomethanol

Methanol is the shortest-chain alcohol and has a LHV of 20 MJ/kg and a HHV of 23 MJ/kg. Several projects have demonstrated the suitability of methanol in ship engines after modification, for instance the Swedish ferry *Stena Germanica* [4]. Required modifications typically comprise the modifying fuel linings and the tank either to stainless steel or via coating to protect against the increased corrosiveness of methanol, and to apply double-walled fuel pipes as a safety mechanism for methanol's low flashpoint [46, 47]. Because pure methanol does not auto-ignite, one promising option is blending methanol with small amounts of a cetane enhancer as MD95 [45].

While there are multiple methods to produce methanol from biomass, one promising technology is gasification [4, 48]. In this process, biomass is heated to 900 °C under the absence of oxygen. The biomass then decomposes into its monomers, which in turn further decompose to synthetic gas (syngas) [4]. Finally, a copper and zinc oxide catalyst makes hydrogen and carbon monoxide from syngas react with each other to form methanol [4]. With first commercial plants becoming available, the technology is currently at a TRL of about 7 [48].

Since gasification decomposes each organic molecule into its constituents, in principle it does not have particular biochemical requirements on the feedstock. As for all thermochemical process feedstocks, biomass with a low ash content is favourable because the minerals may poison the catalyst [49]. However, it should be noted that gasification of biomass requires a large scale facility in order to be cost efficient. One of the main requirements for the feedstock is therefore abundance.

Price estimates for biomethanol are around 21.6 – 30.6 EUR/GJ (2021 estimate: 35 – 40 EUR/GJ) [7, 45]. Nevertheless, methanol and biomethanol prices are subject to (strong) price fluctuations [45]. As a rule of thumb, biomethanol has often been around twice as expensive as its fossil counterpart [44, 45]. The GHG savings are around 81 – 88 % [24].

3.3.3 Upgraded pyrolysis oil

The most mature amongst direct thermochemical liquefaction processes [50], fast pyrolysis produces a biocrude oil that obtains drop-in characteristics after upgrading. Upgraded pyrolysis oil (UPO) has a LHV of 43 MJ/kg and a HHV of 47 MJ/kg. The emissions of NO_x and particulate matter can be decided on via the degree of upgrading [51], though they tend to be significantly below fossil diesel [7].

Fast pyrolysis is a thermochemical process that aims to maximise the liquid output, in contrast to torrefaction for solid products and gasification for gaseous products. This is achieved under the absence of oxygen at temperatures around 500 °C, short retention times of a few seconds and atmospheric pressure [52, 53].

Of the commercial-scale pyrolysis plants mentioned in a recent commercial status study of IEA Bioenergy Task 34 [50], the average production capacity is about 42 ktonnes/yr. The TRL of these plants is 8 – 9, although TRL 9 can only be found in North America.

In theory, pyrolysis can be performed on any type of biomass, including lignocellulosic biomass. However, to achieve the necessary high heat rates, the biomass needs to be dried to below 10 % moisture and milled into small pieces [4]. 'Most advances have been made in converting sawdust and other small woody residues', Bert van de Beld from BTG Biomass Technology Group says [51]. 'In contrast to Fischer-Tropsch, a typical pyrolysis plant may require 50 ktonnes of biomass per year. This fits well into our current biomass system.' For other feedstocks, such as agricultural waste, the TRL is with between 6 and 7 significantly lower [50].

The prices of UPO were estimated to around 18.1 – 42.9 EUR/GJ[4] [7]. GHG savings are between 90 and 95 % [54].

3.3.4 Fischer-Tropsch diesel

FT-diesel is a pure, high-quality fuel that can be tailored to the specific needs of the target application by varying process parameters. It has a LHV of 44 MJ/kg and excellent drop-in characteristics.

It is produced via gasification of biomass to syngas, with a subsequent chain-elongation in the Fischer-Tropsch process. This process has been employed for counteracting limited access to fuels in the past, for instance in Germany during Word War II and in South Africa during the apartheid embargo [4]. Existing installations, however, rely on other fossil resources such as coal or natural gas. For biomass, the maturity of the process is considerably lower. The TRL was estimated to be between 5 and 6 in 2018 [7].

One issue with Fischer-Tropsch is high energy requirements which only render the process feasible at extensive scales and low feedstock prices. 'This is why Fischer-Tropsch plants are built where natural gas or coal are virtually for free.', Bert van de Beld explains. 'Shell constructed a test facility that is already around 1,500 MW, and that is considered too small for Fischer-Tropsch. In general, these installations operate at around 5,000 – 10,000 MW', so Bert van de Beld.

This fact also poses a constraint to the feedstock, as it is required in high abundance. 'If you need more than a million tonnes of biomass per year, questions arise on how to securely guarantee the supply', Bert van de Beld adds. 'We are looking at an investment of well over 500 million, probably even more than one billion, and who will take that risk for biomass?'. He acknowledges that there are research attempts to scale down Fischer-Tropsch processes, which may become promising solutions in the future [51].

The production costs of FT-diesel are estimated to be around 32.5 – 45.5 EUR/GJ[5] [7]. GHG emissions savings amount to 81-88 %.

3.3.5 Lignin crude oil

Produced via a process called solvolysis, lignin crude oil (e.g. Goldilocks® crude oil) is a relatively simple and cheap fuel that consists of partially depolymerised lignin in a solvent, usually methanol (lignin methanol oil, LMO) or ethanol (lignin ethanol oil, LEO). The lignin content within that solvent can be as high as 50 wt.% or even higher, depending on the intended application [40, 44]. Depending on the lignin content, LMO can be combusted in engines that are designed either to run on methanol or on existing marine fuels. Vertoro is currently performing combustion tests with a leading European shipping company to further specify LMO's fuel properties [44]. Lignin diesel oils achieve a LHV of 33 MJ/kg and a HHV of 35 MJ/kg, which is considerably higher than using their solvents in pure form.

For the production, a lignin-rich feedstock is fractionated in a subcritical organic solvent under pressure, where the solvent fulfils the additional function as a catalyst. The resulting fuel is blendable with diesel fuels without any hydrotreatment [4].

According to Svetlana Obydenkova from Vertoro, the main advantage over other second generation biofuels is that the lignin crude oil is economically competitive to conventional fuels while providing required functionality [44]. Their technology is considering converting 30 ktonnes of wood waste per year, which is a commercial scale. Currently, lignin crude oil production is around TRL 6 – 7, and will enter TRL 8 in Q4 2021 [44].

As opposed to the aforementioned thermochemical processes, solvolysis for lignin crude oil can process high-lignin content material as an input. Therefore, woody residues are a preferable feedstock in order to maximise lignin content, but also other lignocellulosic biomass (e.g. agricultural residues) can be used [4]. 'Vertoro's technology serves as a dual actor in the conversion of lignocellulosic biomass: it depolymerises lignin and also allows for separating cellulose', according to Svetlana Obydenkova. These carbohydrates can be further used in an integrated manner, for instance for biochemical ('advanced') ethanol production with yeast strains. This way, both the diesel (heavy-)like and the gasoline-like fuels are produced via a single feedstock processing step and are both bio-based [44].

Due to the lack of data on price estimates, production costs for lignol from fast pyrolysis [55] are taken as a proxy with a heuristic 30 % addition to obtain the minimum fuel selling price [39]. This proxy results roughly in a range from 11.2 to 14.4 EUR/GJ[6]. This price is in agreement with qualitative evaluations in the literature,

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[4] After applying a 30 % heuristic increase from production cost to minimum selling price [39]

[5] After applying a 30 % heuristic increase from production cost to minimum selling price [39]

[6] Based on a conversion factor of 0.82 EUR per USD

where lignin fuels are commonly described as low-cost and almost competitive with fossil fuels [40, 56]. Similarly, there is not much public information on lignin crude oil GHG emissions savings either, but Svetlana Obydenkova states that even with Vertoro's first technology using fossil methanol, the savings are above 65 %, hence RED II compliant. Using the second technology based on cellulosic bioethanol, the savings will be considerably higher [44].

3.3.6 Hydrothermal liquefaction bio-oil

HTL biocrude oil is a promising fuel for the maritime sector, given that its LHV is with 34 – 38 MJ/kg considerably higher than that of pyrolysis crude oil (18 MJ/kg) prior to any upgrading [4, 57]. Therefore, HTL biocrude could fill the niche of low-quality fuels for shipping [4], but also target higher value fuels with considerably less upgrading required.

Hydrothermal liquefaction is, in principle, a solvolysis process that uses supercritical water as a solvent. In contrast to solvolysis with an organic solvent which acts as solvent and catalyst, water simultaneously acts as solvent, catalyst and reactant [4]. The process operates at temperatures around 250 – 370 °C and pressures up to 200 bar [53].

Currently, the TRL of HTL production plants can be classified between 6 and 7, with the new Canfor-Licella plant in British Colombia, Canada and the Silva Green Fuel plant in Norway entering TRL 7 – 8 soon [50]. Developments in HTL are thus behind those in fast pyrolysis.

As the other thermochemical processes, HTL can theoretically process most types of biomass. Steeper Energy, a Danish company that performs pilot studies on HTL, claims that different feedstocks can even be mixed and processed together [58]. HTL's main advantage over other processes is its ability to process wet biomass, therefore removing the requirement to employ energy-intensive drying. Further research is needed on whether low moisture content feedstocks can be integrated competitively in HTL [49].

The minimum fuel selling price of (non-upgraded) HTL bio-oil was estimated to 607 – 833 USD/m^3 [59], corresponding to approximately 14.3 – 19.6 EUR/GJ[7]. According to Steeper Energy, GHG emission savings of HTL bio-oil are above 80 % [58]. This is in line with values found in the literature [60]. With for HFO as fossil fuel comparator, the GHG emissions savings are calculated to be 78 $\pm$ 2 %.

3.4 Fuel comparisons and conclusions

After describing each fuel separately, this section compares the fuels with one another. Often found key properties in fuel comparisons are the aforementioned LHV, HHV and energy density. They describe the energy that a certain amount of fuel releases upon combustion. As both fuel storage weight and volume are limiting, especially for sea-going ships, these numbers serve as indicators for either how often a vessel needs refuelling, or how much additional freight space would need to be sacrificed for maintaining the usual fuelling frequency.

Tab. 2 lists the LHV, HHV and energy density of the considered biofuels and their fossil equivalents. It becomes evident that HFO, despite mediocre heating values, has the highest energy density due to its gravimetric density being close to that of water. All other oils are considerably lighter and thus would result in a higher fuelling frequency. The lowest heating values and energy densities are obtained for LBG/LNG, (bio-)methanol and (bio-)ethanol. LBG/LNG comes with the additional disadvantage of requiring cryogenic storage which is challenging to establish in the hull of ships. Thus, LBG/LNG would sacrifice a considerable amount of freight space. Nevertheless, LBG/LNG carrier ships can benefit from using part of their cargo as fuel, which hence is today's most common and economic application of LNG in shipping. Apart from LBG, biomethanol and bioethanol, the energy densities of biofuels range between 33 MJ/l (HVO) and 36 MJ/l (UPO), which translates to a 15 % to 8 % increase in fuelling frequency over HFO, respectively. It should be noted, however, that these percentages assume the tank volume to be the limiting factor. Efficiency measures, such as well-timed slow-steaming and arrival at the port, can offer significant fuel savings that would allow for counterbalancing fuelling demands.

Bart Somers, engine technology expert from TU Eindhoven, approaches the fuel comparison from a combustion perspective: 'If I had a say in this, we should aim for short-chained alcohols like methanol, ethanol and maybe even butanol (and/or ethers like DME, OMEx), which can be produced from biomass at low carbon intensities in the short future. And then while engines are fine-tuned to those alcohols or ethers, we have time to scale up synthetic processes from carbon dioxide and green hydrogen that produce the same molecules' [46]. Apart from the advantage of being producible from different feedstocks and processes,

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[7] Based on a conversion factor of 0.82 EUR per USD

Table 2: Lower and higher heating values (LHV/HHV) in MJ/kg and energy densities in MJ/l of maritime biofuels and fossil fuel comparators [4, 24].

Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Energy density (MJ/l)
HFO	39	42	39
ULS MDO	43	46	36
Petrol	43	47	32
LBG	48	55	21
Biomethanol	20	23	16
Bioethanol	27	30	21
SVO	37	40	34
FAME	38	40	34
HVO	43	47	33
FT-diesel	44	–	34
UPO	43	47	36
Lignin oil [61]	33	35	–
HTL biocrude	34 – 38	–	–

short-chained alcohols and ethers provide the cleanest combustion regime, according to Bart Somers [46]. ‘The shorter the chain, the less likely the fuel is to create soot. Oxygenates, such as alcohols and ethers, lower the particulate matter emissions even further due to their better air-to-fuel ratio.’ Another advantage of short-chained alcohols could be higher engine efficiencies if used in special combustion regimes: ‘These advanced combustion regimes approach what is called the *Otto-efficiency* because the combustion happens very fast. This also comes with practical limitations, one being that the engine might suffer from this fast combustions and needs to be moderated. Then you enter a delicate discussion.’ Bart Somers concludes: ‘These alcohols and ethers have the promise of higher efficiencies, but there is no sufficient evidence in practice yet. And that the approach is robust, and that engine lifespans will be the same. These latter arguments are very important, but for us as researchers hard to assess’ [46].

Another interesting point of comparison are the carbon dioxide abatement costs. This parameter links the GHG reduction potential of a measure or fuel directly to its economic efficacy. It can be calculated from the aforementioned prices and GHG emissions savings of each respective fuel. The results are shown in Fig. 3, based on Tab. 3. Note that these results are based on publicly available information and often on production cost estimates that were adjusted to minimum selling prices via a commonly used heuristic [39]. The data shown in Fig. 3 thus is to be understood as indicative.

Table 3: Price estimates and GHG reductions from various biofuels in relation to their fossil fuel comparator HFO. If necessary, production cost estimates were converted to minimum selling price estimates by applying a heuristic 30 % addition that accounts for sales and distribution expenses [39].

	Price estimate [€/GJ]	Reference	GHG reduction estimate (vs. HFO)	Reference
LBG	29.9 ± 14.3	[7]	77 ± 5 %	[24]
Methanol	26.1 ± 4.5	[7]	86 ± 2 %	[24]
1G ethanol	20.5 ± 1.5	[7]	55 ± 23 %	[24]
2G ethanol	34.5 ± 3.3	[7]	84 %	[24]
UCO	18.5 ± 2.3	[29]	98 %	[24]
UCOME	23.9 ± 2.4	[29]	87 %	[24]
HVO	28.4 ± 4.2	[32, 33]	86 %	[24]
FT-diesel	39.0 ± 6.5	[7]	86 ± 2 %	[24]
UPO	30.6 ± 12.4	[7]	93 ± 2 %	[54]
Lignin oil	12.8 ± 1.6	[55]	66 %	[44]
HTL biocrude	17.0 ± 2.7	[59]	78 ± 2 %	[58, 60]

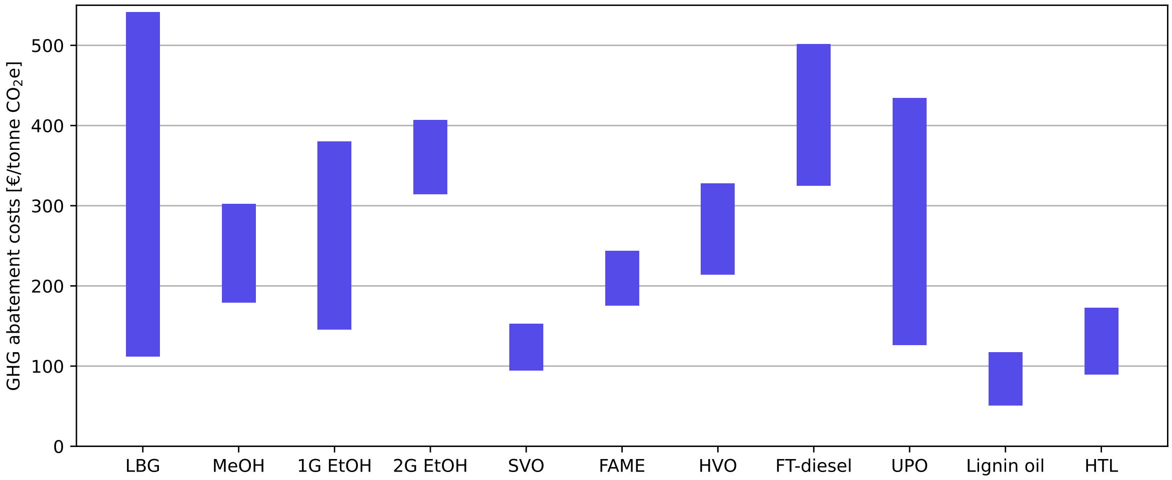

Figure 3: GHG abatement costs in euros per tonne CO_2e from different biofuels. MeOH denotes biomethanol, EtOH denotes bioethanol, 1G denotes from dedicated energy crops and 2G denotes from wastes and residues (‘advanced’). If not stated otherwise, fuels are shown from residues and wastes, such as UCO for the oleochemical fuels. Prices are indicative and based on techno-economic assessments, publicly available market analyses and estimates. The underlying values are summarised in Tab. 3.

One can see that most biofuels occupy a broad range of abatement costs. This is due to their uncertainties in life-cycle GHG emissions reductions and prices, which combinedly propagate to the abatement costs. This renders drawing conclusions difficult and emphasises the importance of contextuality. For instance, LBG may contend with the most affordable abatement options, but it may also be the most expensive fuel for GHG abatement. Which of the scenarios holds true depends on the exact performance of the production plant and the feedstock.

Interestingly, lignin oil, HTL bio-oil and SVO seem to be the most affordable abatement options, the latter of which comes with the aforementioned technical limitations. Furthermore, FAME generally seems to perform better than HVO, although with some overlap between the two. FT-diesel and ethanol are the most expensive options for GHG abatement, with LBG and UPO depending on the context. However, these findings may change as technology advances, for instance if novel catalysts are found that operate more environmentally friendly and cost-effectively. Finally, the choice of fuels is a delicate choice that should include further environmental aspects, e.g. water footprint or land use, as well as social implications of harnessing certain feedstocks. Nevertheless, this overview emphasises that a multitude of options can be made available at reasonable abatement costs.

4 Feedstocks for biofuel production

From the interviews around current knowledge on biofuels and their conversion technology, it became clear that the feedstock is the most impactful parameter in the supply chain of a biofuel, all on an economic, environmental and social level. Therefore, the following section focuses on the outcome of eight interviews that were conducted around part 2 of the analysis – feedstock sustainability.

In general, feedstocks can be divided into four groups: *(i)* (Poly-)saccharides, *(ii)* oils and fats, *(iii)* lignocellulose, and *(iv)* lignin. This can be translated into the following groups of biomass [4]:

1. Carbohydrate crops
2. Oil crops
3. Lignocellulosic biomass
4. Woody biomass
5. Algal biomass

as well as residues of their production and processing. Marine algal biomass is interesting because it is abundant and does not occupy land for growth. However, its processing is complicated with many challenges left in industrial applications, making it a non-viable solution for the fuel sector today [62, 63]. Due to this study's focus on near-term biofuel solutions, the feedstock analysis excluded algae from further consideration.

Jeroen Kroezen from Solidaridad factors in three key points for sustainable biomass for bioenergy: 'First, we look into underutilised residual streams from other sectors such as food production. This allows us to only consider biomass that is truly available. When it comes to dedicated crops, there are many certification schemes for biomass that may serve as an indication how sustainable certain types of biomass are. Another important factor is the efficiency of the crop. For energy purposes we should opt for crops that make efficient use of land and inputs per output' [64]. Which inputs to be considered depends on the local context of the biomass and the agricultural practices on-site [64]. For instance, water consumption is often a concern when growing biomass, but it becomes a key priority in regions with water management issues. 'It is impossible to make a generic statement about sustainable biomass', Jeroen Kroezen says. These findings underline the necessity of a good understanding of the production region and local context prior to deciding on a feedstock.

'For Solidaridad, our main goal in a bioenergy project would be to create an additional value for the farmer and farm-workers. It's part of our social agenda', Jeroen Kroezen adds [64]. Jesus Esparza from Solidaridad acknowledges that not all added value is of financial nature. 'This added value is indeed a nuanced concept. A bioenergy project may also provide electricity or biogas to a community or remove pollutants from their wastewater. There is also knowledge transfer, such as efficient agricultural practices, that helps minimising fertiliser use and thus creates more value for the farmer.'

Carlo Hamelinck from studio Gear Up subscribes to the notion of using certification schemes for sustainability evaluation. He suggests first defining one's own criteria and then comparing which schemes cover them most. 'Sustainability criteria are nothing new, we do not have to reinvent them from scratch' [63]. He stresses, however, that certification schemes not only differ in their considered criteria, but also in scope of feedstocks and geographical coverage. For global bioenergy companies, the ability to apply a scheme worldwide and for a variety of feedstocks may become more important than the completeness of sustainability criteria considered in the scheme [63]. Additionally, Carlo Hamelinck underlines that schemes are under constant development. 'Some certification and auditing have received criticism which resulted in mistrust from several public actors. I think a more useful approach is to improve the schemes and auditing instead by asking what needs to be improved to avoid mistakes in the future.' He further acknowledges that some criticism stems from specific requirements that a global scheme cannot fulfil: 'The more specific you want to be by deviating from certification schemes, the more costly your product will be. And the more costly the product, the less accessible it is to the customers and the certificate will have no impact. That might become an optimisation task' [63]. It follows that the intention to make the most positive impact possible does not translate to strictest sustainability criteria when taking economic realities into account, which is particularly important for a thin-margin sector as maritime transport. The search for sustainable feedstocks needs to follow a multi-criteria approach, taking economic, social and environmental aspects into account.

Carlo Hamelinck concludes with the importance of well-managed fields following good agricultural practices: 'You will always have to look at the plot basis, what is going to be the best crop for me this year, and can maybe precision agriculture help? Can other developments help to diversify the crops to increase the yield in a sustainable way? And independent of the crop I believe it can be done in a sustainable way.'

4.1 Residual streams

The use of residual streams from harvest or other production processes is often pointed out for its contribution to a circular economy and its sustainability. Consequently, the European Renewable Energy Directive incentivises utilising residues for bioenergy by introducing emission savings multipliers to waste-based biomass [24].

Concerning residual streams, Jeroen Kroezen mentions the importance of identifying pre-existing uses of the particular residue. Even though coffee husks and bagasse from Brazil are often mentioned as interesting waste streams, they already fulfil a local function. Coffee husks are locally mixed with coffee beans for local coffee production, while high quality coffee beans are exported, whereas around 80 % of Brazilian bagasse is used for electricity and heat production [64]. Luis Cutz from Delft University of Technology made a similar observation: 'Straw from cereal production is often advised in a European agricultural residue context. But when you travel around the European countryside, you can see that there is no straw available. It is either used for feed or bedding, and I was told in Denmark there was a time when straw had a price of 90 EUR/tonne, which makes your bioenergy process really costly' [49]. In both cases, often promoted residue streams already have a local market that a bioenergy project adds a new competitor to. 'We have to carefully analyse the current situation and usage of substantial waste streams. And if you intervene by taking out part of that waste stream, what are the consequences?', Jeroen Kroezen concludes.

Nevertheless, unmanaged residues can also pose threats to humans and the environment. This is where the full potential of waste valorisation comes into play. 'If you leave too much biomass on the soil, it starts rotting and produces carbon dioxide and methane' [64], a 28 – 36 times more potent GHG than carbon dioxide [65]. 'It also increases the likelihood of catching fires which may even propagate into forests', Jesus Esparza notes. Therefore, some certification schemes such as Bonsucro defined optimum retention amounts for top leaves and twigs to restore soil carbon and nutrients without overfertilising and risking rotting on the fields [64]. Another example is the potential of valorising pest control. Encroacher bushes are a serious pest in various countries, like for instance in Tanzania. By adding a market demand to them, pest control can go hand in hand with bioenergy production and socio-economic development [66].

When striving for an added value to the primary producers, cascading may be applied in order to prioritise high-value applications. However, Mark Brown from IEA Bioenergy notes that 'then the question arises what a high-value application is' [67]. From an economic point of view, this question is easily answered. Pharmaceuticals and specialty chemicals are on the top, materials and bulk chemicals below and energy is on the bottom. Certain harder-to-abate sectors such as maritime transport or high temperature heat can be defined as higher-value energy applications, but are still considered a lower value application than materials [68]. Nevertheless, when adopting a climate perspective that aims to minimise GHG emissions, the energy and heat sectors rise to the top of the cascading chain [6], as these two sectors contributed with 73.2 % to global GHG emissions in 2016 [69]. This discrepancy can be addressed by the application of a multi-criteria approach that considers economic, environmental and social parameters altogether. Such approach is further described in Sec. 6.5.

4.2 Logistics around biomass

One often mentioned challenge to producing biofuels is the security of supply and the logistics and transport of biofeedstocks. 'Biomass supply is fundamentally different from continuous fossil oil extraction.', John Posada Duque from Delft University of Technology states [70]. 'The harvest is seasonal and may vary significantly per month. Biorefineries might face off-season downtimes, which highly impact the economics.' John Posada Duque gives the example of Brazilian ethanol biorefinieres from sugarcane. 'They overcome this problem with their large scale. The plants can deal with the high availability of sugarcane during the harvest season, which allows to produce enough ethanol to compensate for about 4 months of downtime per year.'

Luis Cutz adds the importance of distances to the discussion. 'Transportation of biomass is a crucial factor, not only regarding cost-effectiveness, but also regarding the quality of your resulting biofuel' [49]. He gives the example of woody pellets, which cannot be produced in sufficient quantities in the Netherlands. 'Even with dried and compressed biomass, it degrades eventually. And this becomes an issue when you have to import biomass from abroad, which may take 6 – 9 weeks or so' [49]. Luis Cutz stresses the problems arising from that. 'You might end up paying a high price for high quality biomass, but instead you receive a partly degraded product that your bioprocess is not optimised for' [49].

4.3 Availability of biomass

Whether sustainable biomass is available or can be made available in meaningful quantities is often debated. A joint fact-finding study of the Netherlands Environmental Assessment Agency, based on over 400 academic papers and reports and over 150 Dutch stakeholders, recently revealed the impact of different views about biomass on the estimates for its availability [6]. Their research suggests that even in the more conservative views towards biomass, the Dutch energy requirement is reasonably coverable with global or European biomass availability. However, the Netherlands would depend on imports of biomass. With global availability of biomass from agricultural and forestry residues being estimated at 95.4 EJ/year, rising to 129 EJ/year in 2030 [6], one can see that biomass may be able to fill the needs of the global transport sector or at least a large share of it. Global transport energy demand has been estimated to about 100 EJ/year in 2015 [71].

Nevertheless, this availability will have to be harnessed in a sustainable way while taking into account the aforementioned logistical challenges. This includes making special use of areas where there is a concentration of residues, i.e. highly productive bioregions. For Europe, Wageningen University & Research (WUR) has created an interactive geoinformatics tool S2Biom that allows identifying such highly productive regions by quantifying their biomass throughput [72].

4.4 Conclusion

It follows that the search for sustainable feedstocks is the key task in every bioenergy project, as the choice of biomass decides the economic, environmental and social impacts of the resulting energy carrier. The choice of biomass is a delicate task that requires careful consideration and forecasting possible side-effects from the use of a certain feedstock. One-dimensional approaches, as in e.g. high-value cascading or merely considering GHG savings, need to be applied with caution. A multi-criteria approach offers more benefits, as it simultaneously targets all three pillars of sustainability (economic, environmental and social) while providing a structured, transparent and comprehensible decision process. Svetlana Obydenkova stressed the importance that 'everything should be considered from a system's perspective' [44]. Similarly, the choice of feedstock may be regarded as a system rather than a certain crop or residue. A system that specifically targets sustainable bioenergy production from inclusive value chains is the concept of biohubs [73]. These biomass-producing clusters are further described in the following chapter.

5 Biohubs for inclusive supply chains

The ambitions for a transition of Europe and its Member States towards a bioeconomy gave momentum to several studies on the availability of sustainable biomass [6, 74]. Nevertheless, 'social aspects are often not sufficiently addressed in the biofuel debate and legislation', Jesus Esparza from Solidaridad notes [64]. To ensure both environmental and social sustainability of feedstocks, the concept of *biohubs* was developed during the biomobilisation (BioMob # 1) expert session organised by the Netherlands Platform for Sustainable Biofuels.[75, 76].

Biohubs are clusters centred around sustainable and socially-just biomass production for food, feed, and non-food purposes (see Fig. 4). Rather than simply extracting biomass for upstream use, a biohub provides an exchange by transferring knowledge and technology into the region. According to Patricia Osseweijer, 'the primary goal of the biohub is to create and facilitate social development' [73]. This is achieved via diversifying the primary producers' income as they enter the bioenergy market, as well as by circular nutrient and water management within the region. 'The novel idea around biohubs is to not consider biomass just as a commodity that is transported to a refinery and converted, but to build that into a local context', said Patricia Osseweijer. Impacts are to be regarded on a landscape level, where the biohub contributes to improvements in biodiversity and soil health [75]. In the following years, the biohub concept will be further specified and operationalised as part of the NWO Science project 'CLEAN SHIPPING' [77].

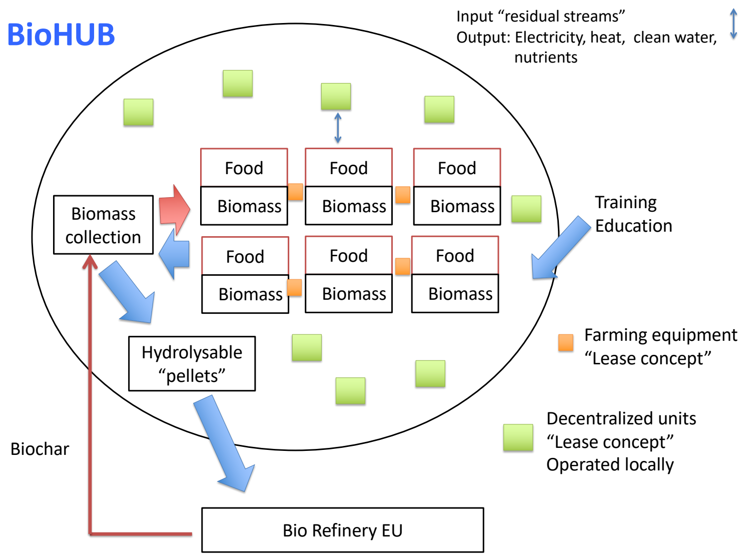

Figure 4: An illustrative concept of interactions and flows within a biohub [75]. Numerous smallholders produce food, feed, biomass and fibre, with the biomass being commoditised in decentralised valorisation units and then shipped to a centralised large-scale refinery. In exchange, farming equipment and decentralised biomass valorisation units are provided via lease concepts. Nutrients are recycled by returning biochar to the soil of origin.

Francis X. Johnson from Stockholm Environment Institute (SEI) adds that 'one basic concept of circular bioclusters is the economy of scope as a counterpart to the economy of scale' [78]. Via a diversity of products, processes and applications, biohubs can be made more resilient over time, according to Francis X. Johnson. 'Biohubs can be low-tech as well, as long as they are multi-functional, multi-product and integrated in socio-economic terms'. When considering socio-economics carefully from an early stage, the farmers gain more security via a secured demand and stable supply chains. This may also help resolve issues with public acceptance that biofuels currently face [75, 78]. As an example of a biohub, Francis X. Johnson mentions the Food Valley of Bjuv in South Sweden, which is focused around the circular production of healthy food products at a low environmental footprint [79]. 'But there is no reason they couldn't add energy products once they operate at a larger scale. It is possible', so Francis X. Johnson. As a challenge for biohubs, he mentions the difficulty in logistics when catering to different sectors (such as food, feed, fuel and fibre) at once. Another challenge is to balance logistics and shipping to remote areas with limited infrastructure: 'it is always going to be cheaper if you have a density of demand'. He notes that especially in shipping, demand is distributed in a different way as other fuel markets, with large-scale bunkering stations needed in few concentrated areas.

A recent study by IEA Bioenergy Task 43 provides the outcomes of a dedicated workshop on the SWOT (strengths, weaknesses, opportunities, threats) of current biohubs [80]. 'We tend to take an inclusive definition of the biohub', Mark Brown from IEA Bioenergy says [67]. According to Mark Brown, 'a biohub is any point in the supply chain that either facilitates the amalgamation of different sources of biomass, that in some way there is a value-adding process to the biomass or it supports the distribution to multiple end-users. It becomes a node, if you will'. By this definition, there are numerous examples of biohubs to be found today, e.g forestry industries in Canada, Sweden and Finland, or agronomy in Eastern Europe [67, 80]. Today's biohubs are mostly 'driven by a particular commercial interest within their region and they tend to be very region-specific', so Mark Brown. 'They are trying to make the biomass supply more reliable and more cost-effective'. Despite the differences in definition between the biohub concept of the BioMob # 1 and the concept of IEA Bioenergy, there is an overlapping commonality: 'A biohub creates a concentration of biomass from multiple sources, and that gives more confidence to the market that it is consistently going to supply', Mark Brown concludes. He adds that market prices and quality expectations can be met more easily in biohubs, for instance by mixing higher and lower cost or quality material to obtain overall a better average [67].

Considering the length of the supply chain, he replies 'Nothing we produced from this point indicates that a biohub influences the distance you can transport over a traditional supply chain. Although, there is some speculation that e.g. a mobile pyrolysis plant close to the source with subsequent transport of the pyrolysis oil may extend the manageable length of bioenergy supply chains'. Generally, IEA Bioenergy's research consistently found that lignocellulosic biomass supply chains beyond 100 to 120 km, in some exceptional cases up to 150 km, tend not to be economically viable [67]. This finding stresses the importance of building biomass supply chains into the local context.

The findings of the SWOT analysis conducted by IEA Bioenergy Task 43 can be seen in Fig. 5.

TOP STRENGTHS

- Availability of sustainable biomass
- Good quality and quantity of feedstock
- High skilled workforce
- Provides economies of scale (potential to access multiple end markets for a range of end products)
- Established infrastructure and primary assets

TOP WEAKNESSES

- Complex intergovernmental structures and priorities (federal/provincial)
- Limited access to capital in an uncertain environment (regulations, policies, access to fibre)
- Lack of market for bio-based products
- Lack of accurate spatial inventory data
- Indigenous relations

TOP OPPORTUNITIES

- Underutilised feedstock
- Entry point for non-traditional players to be involved in the bioeconomy
- Emerging carbon markets (value on carbon) could create new demand/value for products (from bio-hubs)
- Economies of scale allow access to new markets and attracts investments
- Ability to leverage HQPs, infrastructure and markets from other sectors

TOP THREATS

- Uncertainty (impacts of climate change, policy support, markets, etc.)
- Past failures of bioeconomy projects leading to no (or low) investor confidence
- Inability to launch a national bioeconomy strategy
- Traditional forest sector industry declines and/or collapses
- Increasing frequences and impact of natural disturbances

Figure 5: IEA Bioenergy consensus SWOT analysis' results for existing biohubs in Canada by IEA Bioenergy's definition [80].

As a technical solution to the biohub concepts, Bert van de Beld from BTG Bioliquids mentions: 'This is the basis of pyrolysis. It can be seen as an intermediate, coupling the agro-industry with the chemical industry. Biomass producers prefer working with solids, the chemical industry prefers working with fluids, and we do the conversion.' As an example for decentralised biocrude production and centralised upgrading, Bert van de Beld refers to the Preem refinery in Sweden. 'They will start with crude pyrolysis oil next year, which comes from one plant, the PyroCell plant. But they still have more capacity in their FCC, which is why they are considering the additional input of other pyrolysis plants. In that case, they will receive pyrolysis crude oil from different plants with different feedstocks.'

Another technical solution is biogas production, according to Wolter Elbersen: 'Anaerobic digesters can be operated at a farm level, relatively decentralised. Part of the biomass such as sugars, fats, starch but also hemicellulose and part of the cellulose can be converted to biogas. The remaining persistent fibrous material and minerals will have more value for the soil than the easily digested material. Fibrous material will provide water holding capacity and cation exchange capacity. The minerals such as N, P and K, Ca, Mg are plant nutrients. Producing biogas first and using digestate for the soil will probably not decrease the value for the soil.

The quickly accessible matter is converted into biogas, whereas the more persistent lignin stays together with the nutrients in the digestate, suitable for the use as fertiliser. This type of persistent matter has much more potential for restoring soil carbon than the quickly accessible matter.' [81].

6 Feedstock selection approach

The feedstock's priority in establishing sustainable biofuel supply chains has already been argued above. Based on the conducted interviews and the literature, a structured research approach for finding sustainable feedstocks is worked out in the following. The approach has been further refined based on feedback from Solidaridad [64] and the NWO 'CLEAN SHIPPING' project consortium.

The procedure for the structured feedstock selection is shown in Fig. 6. Starting from the region and market, a stakeholder analysis is conducted wherein key stakeholders are identified and conflicting values are analysed. Afterwards, a landscape analysis provides insight into different land uses of the region, the climate, ecology and the condition of the soil. From thereon, bioenergy crops are considered as well as existing residues within the region. Comparing a selection of promising residues against a selection of promising dedicated crops then allows for finding top candidates. Since such a comparison requires multi-criteria consideration, the Analytical Hierarchy Process (AHP) is suggested for making such decision.

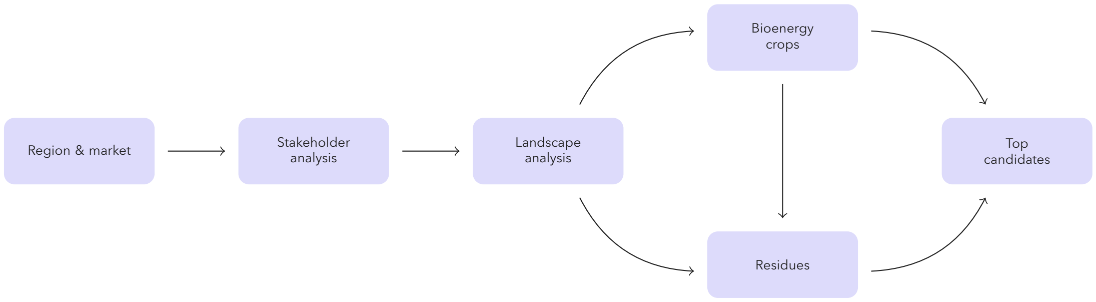

Figure 6: Structured feedstock selection approach.

It should be noted that finding sustainable feedstocks is an iterative process that may require extending or eliminating factors from the preceding landscape and stakeholder analysis. It is shown here as a linear approach for simplicity.

The following subsections will explain each step of the structured research approach more in detail.

6.1 Region and market

Due to the innumerable variety of potential feedstocks, the search requires significant scoping early in the decision process. In this approach, defining a region and a market is recommended, as these two factors are usually decided on based on various other factors, such as experience, partnerships, contacts, promising fuel market or favourable legislation, to name a few.

By defining the region for biomass production as well as the biofuel market, both the supply chain's beginning and its end are defined. This puts the biofuel in a political and socio-economic-environmental context. Any produced biofuel will have to comply with both the regional and the target market's laws, regulations and ambitions in order to be accepted. Indirectly, the scope of production is also set by choosing a region and a market, as there is limited market demand and limited biomass supply dependent on the productivity of the region.

6.2 Stakeholder analysis

The goal of the stakeholder analysis is to identify social aspects that are relevant for the production of biomass in the particular regional context. To gain insight into the regional social context, key stakeholders in the value chain of biofuel production are identified. Subsequently, a power analysis is conducted to analyse which key stakeholders have access to land and which stakeholders are vital to decision-making processes [64]. Based on power and interest, the stakeholders are mapped and their interests and values are determined via interviews or surveys. This allows for the identification of possibly diverging or conflicting interests, and how to resolve these conflicts by introducing the biofuel project into the region.

6.3 Landscape analysis

The landscape analysis aims to gather knowledge on the environmental context of the biomass project. It starts with analysing the land uses within the region, such as the percentage of marginal, abandoned or degraded land, and the general distribution of agricultural, forestry, urban and natural land. It then continues by depicting the climate and ecological factors. The current and future climate scope the choice of crops that can be grown efficiently in the region. Ecological factors may entail pressures on biodiversity in the current landscape, or potentially harmful land uses or practices. Furthermore, regional input may help gain insights into which role abandoned land plays for habitats, especially for protected or declining species.

The landscape analysis allows finding crops that may benefit the environment, e.g. by improving soil conditions or by forming synergies with other crops to make them more resilient against climate change. Factors to take into account are the water needs and the depth of the roots in comparison to local plants. Invasive or potentially invasive species are to be discarded from the analysis.

6.4 Bioenergy crop and residue analysis

In the European context, the use of waste material for bioenergy is often highlighted. However, growth of dedicated bioenergy crops may bring additional advantages or ecosystem services that waste streams cannot provide [63, 82]. If there is underutilised land in the landscape, for instance caused by land abandonment, cultivating dedicated bioenergy crops may help recover the soil and its ability to sequester carbon [82]. From an iLUC perspective, the recovery of abandoned land is the preferable choice over the valorisation of waste [6].

Since the choice between dedicated crops or residues is contextual, it should become clear from the landscape analysis which of the options is preferred. Generally speaking, a list of promising bioenergy crops should be compared against a list of promising residues for bioenergy production. Residues may encompass agricultural or forestry residues, but also industrial, food, or municipal residues. However, ‘in order to maximise the additional value to the primary producers, agricultural and forestry residues should be prioritised over residues that occur further down the supply chain’, Jeroen Kroezen from Solidaridad mentions [64].

6.5 Analytical hierarchy process

After a list of feedstocks is compiled, a choice that relies on multiple criteria (economic, environmental and social) must be made to choose the best performing feedstock. Analytical hierarchy processes (AHP) provide a methodological approach to facilitate such decision processes. An AHP starts by defining a goal to the problem, and then continues by defining general criteria (for instance profit, planet, people). Subsequently, each criterion is assigned a set of quantifiable subcriteria that promote their superordinate criterion. Each of the subcriteria is assigned a weight factor, which are determined by surveys of key stakeholders that ideally form a fair representation of all parts of the supply chain. Using these weight factors, the best performing feedstock can be determined. More detailed explanations on how to apply AHP can be found elsewhere [83, 84].

Fig. 7 provides an example of how an AHP could be conducted for a feedstock selection that aims to incorporate biohubs. The listed subcriteria may serve as a starting point for identifying suitable feedstocks, but they require adaptation to the biofuel project’s specific goal as well as the regional and market context. For instance, a biofuel targeted at the European market should include RED II compliance as a subcriterion.

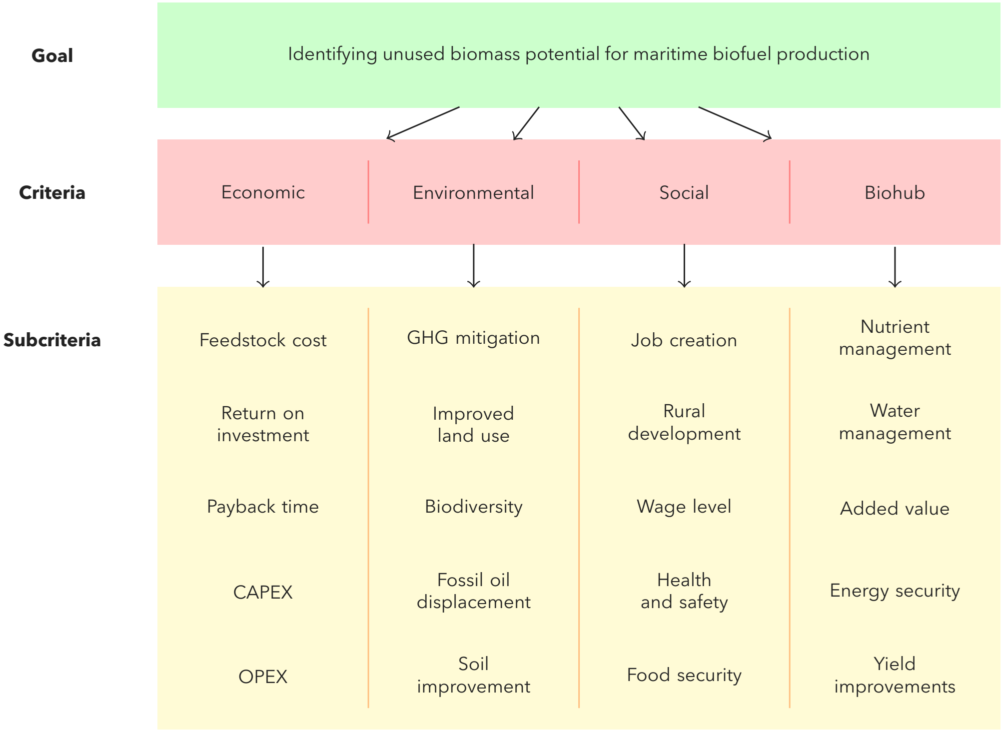

Figure 7: Analytical hierarchy process (AHP) for the selection of sustainable feedstocks.

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