

# - IDEALFUEL -

Lignin as a feedstock for renewable marine fuels

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## Deliverable Report

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## **Publishable summary**

IDEALFUEL, EU H2020 project, aims to develop a Biogenic Heavy Fuel Oil (Bio-HFO) that can be used as drop-in within the existing maritime infrastructure. As technical developments progress, it is necessary to assess the market for successful penetration. In this report, an overview of the market is presented together with the instruments that can affect the market up-take of the Bio-HFO.

This reports assesses the following aspects, with the perspective of the European Economic Area, namely: legislation, mandates and incentives; emission performance; fuel compatibility and blend-ability; and production cost. Cost is currently a determining market driver. Nevertheless, it is important to consider how the legislative frameworks that are currently in development will affect it. Moreover, the potential reduction in emissions will be translated into marketing advantages, whether by branding or premium benefit. Finally recommendations are given and potential risks are identified.

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## Abbreviations

Symbol / short name	
GHG	Greenhouse Gases
IMO	International Maritime Organization
EEA	European Economic Area
UNFCCC	United Nations Framework Convention on Climate Change
MARPOL	International Convention for the Prevention of Pollution From Ships
UN	United Nations
ECA	Emission Control Areas
NOx	Nitrogen Oxide
SOx	Sulfur Oxide
VOC	Volatile Organic Compounds
PM	Particular Matter
RED	Renewable Energy Directive
ILUC	Indirect Land Use Change
HBE	Hernieuwbare Brandstofeenheden
EGD	European Green Deal
ETS	Emission Trading System
HFO	Heavy Fuel Oil
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
MDO	Marine Diesel Oil
HVO	Hydrotreated Vegetal Oil
FAME	Fatty Acid Methyl Ester

## 1 Introduction

### 1.1 Background IDEALFUEL Bio-HFO

The maritime industry is a growing business, which accounts for 12 % of total transport global energy demand with a significant share on CO<sub>2</sub> emissions (Balcombe et al., 2019). Currently, it represents 940 million tonnes of CO<sub>2</sub> emissions globally (Abdenur, 2021). Although efforts have already taken place to reduce in 8% the CO<sub>2</sub> emissions between 2008 and 2015, there is room for improved practices. According to the International Maritime Organization (IMO) and considering the business-as-usual scenario, emissions are expected to increase 50 % to 250 % by 2050 (Abdenur, 2021; ECSA, 2020).

The decarbonization of the shipping industry is a challenging task, which requires innovative solutions, particularly, towards advanced “drop-in” biofuels (ECSA, 2020). Advanced biofuels have been defined according to the Renewable Energy Directive II (RED II), as those produced from the feedstocks listed in of Annex IX part A of the RED II (European Alternative Fuels Observatory, 2020). Compared with other renewable options (e.g., electricity or hydrogen), advanced biofuels are the most effective solution for the immediate reduction on GHG emissions, safe keeping the compromise with 2030 targets. Advanced biofuels are considered an essential part of the European roadmap for decarbonization, their use can decrease the dependency on fossil fuels while adding value to secondary materials that are considered of non-value, such as residues (Panoutsou et al., 2021).

Currently less than 1% of the fuel used in marine transportation is bio-based. This is mostly due to the considerably lower price of fossil fuels alternatives. Moreover, the fuel consumption profile in the shipping sector is largely depended on the price of residual fuel oil, one of the cheapest available fuel (Uslu, 2019).

Advanced biofuels face mayor challenges for their widespread adoption in the shipping sector, namely cost and availability. Their cost is roughly 2 to 5 fold higher compared with crude-based fuels. The second barrier, availability, refers to the current lack of production capacity to meet the global demand (IRENA, 2019). Within this context IDEALFUEL (EU H2020 project) was conceived with the overall objective of producing an advanced and cost-competitive biofuel (Bio-HFO) out of lignin. With this concept in mind, a new process has been developed to fractionate lignocellulose and extract lignin, suitable for further upgrade into a marine fuel. Although lignin is accessible in the market, the chemical characteristic do not meet the necessary requirements for the efficient production of the end product. Moreover, the use of the available residual stream of lignocellulosic biomass is a way to cope with the circular economy while adding value to the whole project.

## 1.2 Objective

The objective of the present report is to provide valuable information on the market perspective and, therefore, support the best process design and R&D strategy. This report presents the size and trends in our current market, legislative instruments, potential market competitors in the near and long term, opportunities and constraints. It is expected that, by the end of this report, a clear overview of the market is provided, identifying a potential spot for Bio-HFO within an European market context.

## 1.3 Outline of Report

The report is structured as follows. In section 2 the European legislation which might directly or indirectly affect the market for the Bio-HFO is presented. Then, in section 3 it is discussed the present fuel landscape in the shipping sector, encompassing liquid fossil fuels and alternative fuels. This section discusses fuels' specifications, compatibility and emissions of current and future fuels. Section 4 presents an overview of the future market based on scenarios developed by the EU, elaborating on pricing and possible future competition. Key stakeholders that can influence the market uptake are also discussed. Finally, conclusions and recommendations are provided based on the findings.

## 2 Socio-economical Context

In this section, the regulatory framework with regard to the European Economic Area (EEA) is discussed. Legislative mandates are considered one of the most important market drivers for advanced biofuels, since they might shift future market trends, securing or limiting biofuels' share. However, as it is presented below, the effect of the legislatives mandates on the maritime sector is still in discussion. For the moment, they can be considered useful guidelines for the future, which are constantly under revision.

On the social side, it is considered that advanced bioenergy can stimulate jobs creation, local development and contribute to energy supply security. Feedstock diversification can guarantee that fuel demands are met, while triggering industrial competitiveness. Due to these potential impacts public perception together with political regulatory measures strongly influence the development of a bio-based market (Schröder et al., 2018).

In this sense, biofuel market development is equally dependent on technology and on the socio-political and environmental context. Consequently, the limited aliment of traditional biofuels to these aspects is reflected in the observed preference of social-political framework towards advanced biofuels (Lucia & Ribeiro, 2018).

### 2.1 Regulatory Frameworks

Regulatory frameworks play an important role in setting targets and imposing restrictions. They are key to stablish the criteria that the fuels should meet and have a large influence in the market (EurObserv'ER, 2019; Panoutsou et al., 2021). Although advanced biofuels have a large potential to mitigate CO<sub>2</sub> emissions, their production is usually more expensive than the fossil equivalent due to the lower technology maturity and scale. Market interventions, therefore, are essential to leverage the use and acceptance of advanced fuels (Panoutsou et al., 2021). In the case of IDEALFUEL's Bio-HFO, international regulation set by the International Maritime Organization (IMO) and the EU directives will have a large influence on market opportunities.

#### 2.1.1 International Convention for the Prevention of Pollution from Ships (MARPOL)

Due to its international character, emissions coming from the shipping activities are not attributed to any nation. The responsibility for governing GHG emissions falls under the United Nations Framework Convention on Climate Change (UNFCCC), particularly in the United Nations (UN) specialized agency IMO (Sikora, 2020). The IMO's primary purpose is to establish and maintain a comprehensive regulatory

framework for shipping, covering, amongst others, maritime safety, environmental concerns and the efficiency of shipping (Uslu, 2019).

The International Convention for the Prevention of Pollution from Ships deals with environment and pollution related to marine activity. It was adopted in 1973, modified by the MARPOL Protocol in 1978 and entered into force in 1983. MARPOL has been updated by several amendments throughout the years. The Convention includes six technical Annexes that covers the regulations to prevent and minimize pollution prevention from accidental or daily operations. Special Areas, practices and restrictions are described in most of the Annexes (Brodie, 2020)

In 2005, air pollution was specially addressed by setting specific limits on emissions, and by the establishment of the emission control areas (ECAs). ECA zones (depicted in Fig .1) have a stricter limit for emissions of nitrogen oxide (NO<sub>x</sub>); sulfur oxide (SO<sub>x</sub>); volatile organic compounds (VOC); and particular matter (PM) (see table 1). Limits in the sulfur content of the fuel were reduced from 3.5 % to 0.5 %. Within specific designated ECAs the limits were even stricter (0.1 %) (IMO, 2020). There are two possible alternatives to reduce SO<sub>x</sub> emission namely, the use of low sulfur fuels or scrubbers. This is particularly relevant in the context of IDEALFUEL, since low sulfur fuels can benefit from a premium price.

Table 1. Annex VI NO<sub>x</sub> emissions limits by Tier

Tier	Date	NO <sub>x</sub> Limit [g/kWh]		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17	45 · n <sup>-0.2</sup>	9.8
Tier II*	2011	14.4	44 · n <sup>-0.2</sup>	7.7
Tier III**	2016	3.4	9 · n <sup>-0.2</sup>	1.96

\*Apply for areas outside ECAs. \*\*Apply in ECAs

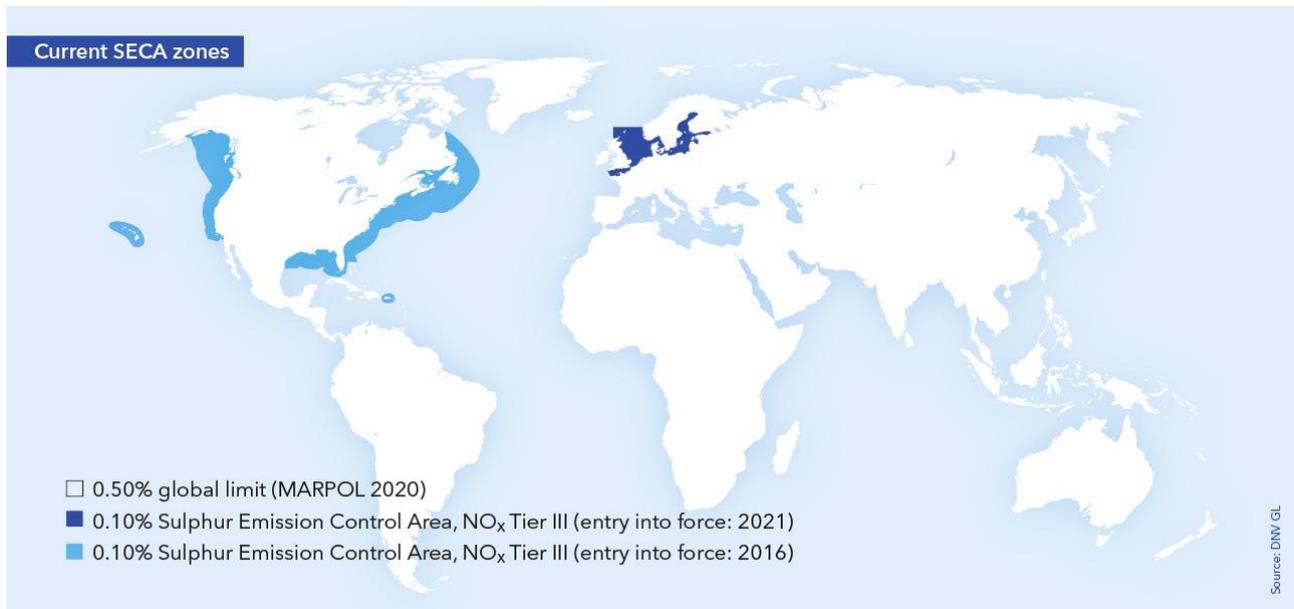


Figure 1. Emission control areas (ECA) ( Source: DND GL).

In 2018, IMO adopted the strategy to reduce the GHG emission by 40% in 2030 and 50% in 2050, with respect to 2008 baseline (Sikora, 2020; Yuanrong Zhou, 2020). Consequently, it is expected a high investment in R&D, infrastructure and trials to support the development of new technologies and fuels to meet such targets (International Maritime Organization, 2019). Revision on the strategy adopted for GHG mitigation is expected by 2023, when updated directives will be considered in global scale by IMO (Yuanrong Zhou, 2020). With these regulations in place, it is estimated that approximately 70% of the current fuels in the market will need to be changed to sustainable fuels to cope with the targets (Uslu, 2019). At European level, the targets and goals for the maritime sector are still under definition. Below are described the current and future legislatives instruments that might have influence on renewable fuels in the maritime sector.

### 2.1.2 Renewable Energy Directive (RED)

The Renewable Energy Directive (RED) was introduced in 2009, with the aim of promoting renewable energies in the EU. At first, it established that 10 % of the energy in the transport sector should be obtained from renewable resources. In 2015, it was modified by the EU Indirect Land Use Change Directive, imposing a limit of 7 % over those fuels coming from resources that could potentially compete with food production, e.g. soy. Later a target of 0.5 % for advanced biofuels was introduced (Panoutsou et al., 2021).

In 2018, RED was revised and RED II came into effect. The RED II provided, for the first time, a roadmap with specific sustainability criteria and targets for biofuels. The revised version increased the target for total renewables to 14 %, and to 3.5 % for advanced biofuels in 2030, also introducing the double counting approach. The double counting approach states that advanced biofuels have their contribution accounted

twice in the GHG balance. The use of fuels produced from feedstocks that do not cope with food security and/or represent a potential risk for land use change, will be gradually dismissed by 2030. Some EU member states, however, pledge the non-use of traditional feedstocks before 2030. The Delegated Regulation (EU) 2019/807, supplementing the RED II, fosters the use of resources with low risk for Indirect Land Use Change (ILUC) and which promote improved agricultural practices (Panoutsou et al., 2021).

Annex IX of RED II conveys to edible feedstock for advanced fuel production. As for annex IX, advanced biofuels are mostly produced from residual streams. Much attention is given to this topic since it is a sensible step towards sustainable biofuels production. The sustainable use of lignocellulosic material for energy application is dependent on how and where such material is derived. The direct or indirect land use change (LUC) refers to potential impact that commercial cultivation might have on the availability of productive land, suitable for food production, and the displacement of natural vegetation towards the commercial application. While the first debates on food vs fuel matter, the second leads to GHG emissions prevented from natural carbon stocks and the loss of biodiversity (Stappen et al., 2011). Moreover, the management of any agricultural crop must deal with the depletion of soil nutrients and, consequently, the use of fertilizers increasing its carbon intensity. This must be considered under critical assessment together with the expansion of agricultural areas. On the other hand, the use of dedicated energy crops on degraded and marginal lands can contribute to improve soil fertility, and could be a strategy to increase feedstock availability, as suggested by the Delegated Regulation (EU) 2019/807. Nevertheless, the definition and classification of degraded lands still lacks clarity (Thomas et al., 2021).

It is vital, therefore, to consider the use of agricultural residues when discussing the use of lignocellulosic material for energy purposes. The valorisation of agricultural and forestry residues is fundamental to increase bioenergy capacity and boost the value added to the feedstock without land area expansion. Therefore, mitigating the matters related to agricultural practices and land use change.

In Annex IX of RED II, Part A, are listed some lignocellulosic feedstocks, available for advanced biofuels production: such as straw, bagasse, husk, nutshells, cobs, forestry residues and non-food cellulosic material. Those outside of this list are not considered for advanced fuel production; therefore, the emissions attributed to production phase are accounted (European Parliament, 2018). It is valid to mention that annex IX is currently under revision and discussion. The addition of feedstocks is expected but not certain. Furthermore, it is likely that additional criteria might be used while defining the eligibility of feedstocks for advanced fuel production.

It is expected that Member States will transpose EU directives into their national framework, in order to account for the relevant national particularities. In the incorporation process differences might take place between Member states, for instance defining the obliged groups.

RED sets important criteria that the Bio-HFO should comply with in order to be considered an advanced biofuel. The recognition by the EU and a certification scheme are, therefore, necessary in order to benefit from market incentives related to sustainability performance.

#### *2.1.2.1 Renewable energy units - Hernieuwbare brandstofeenheden (HBEs)*

As directive, the RED had to be transposed into national law. In the Netherlands, a system of renewable energy units (HBEs: hernieuwbare brandstofeenheden) was established to ensure compliance with the annual obligation renewable energy obligation and GHG emissions reductions in transportation. One HBE represents 1 gigajoule (GJ) of renewable energy that is delivered to the Dutch transport market. HBEs are created by claiming deliveries of renewable energy. Under the Energy for Transport compliance system, the Dutch government uses a trading system where participants can cooperatively deliver their mandatory share of renewable energy in the most cost-effective way. There are different types of HBEs depending of the raw material used for fuel production. The mandatory use of advanced HBE over conventional and the preference of high value applications (over heat), are beneficial for the production of advanced biofuels (Rijksdienst voor Ondernemend Nederland, n.d.).

Even though shipping was not subject to the GHG emissions reduction obligation, the shipping sector was included into the system via creation of voluntary HBEs (so-called “opt-in”). The intention behind was to foster the development of sustainable solutions in the shipping sector. In 2020, around 19 million HBEs were created in the shipping sector. Since the start of 2021, only advanced biofuels (produced from feedstocks of Annex IX Part A RED II ) are eligible to create HBEs. In the Netherlands, double counting is applied to advance biofuels to further incentivize g the use of these types of biofuels. This trading system is currently only implemented in the Netherlands. Other EU countries have no such system or mandatory legislation for the use of advanced biofuels in the maritime sector

#### **2.1.3 European Green Deal (EGD) and Fit for 55**

In December 2019, the European Commission announced the European Green Deal (EGD) which set the blueprint for a transformational change. All 27 EU Member States signed to the roadmap towards a climate-neutral economy. The goal of the EGD is to reduce at least by 55 % the emissions in 2030, with respect to 1990 levels. Then, gradually move to carbon neutrality by 2050. The EGD is an instrument of change, that introduces a new policy principle “Green oath: do no harm”. Other EU initiatives must be aligned to this principle (Sikora, 2020). The EGD was implemented through the announcement of the Fit for 55 Package in July 2021 (European Commission, 2021b).

Fit for 55 is a comprehensive package of a dozen legislative proposals aiming for 55 % reduction in emissions in diverse sectors by 2030, compared to 1990 levels. The shipping industry was included in the scope of this comprehensive package proposals, mainly via the following policies:

### **1. The revision of the Renewable Energy Directive II**

It aims at continuously scaling up the usage of renewable and low carbon fuels in the EU. The above mentioned 14% share of renewable energy for transport and the sub-target of 3.5% for advanced biofuels (which are subject to double counting) are replaced by a 13% GHG intensity reduction target for transport with a sub-target of 2.2% for advanced biofuels in 2030. The principle of double-counting will no longer apply. (European Commission, 2021a).

Sustainability criteria and standards for reliability, transparency, certification and verification will most likely not change. For the case of IDEALFUEL, certification of the fuel will play a key role for its use. The mayor impact will most likely be related to the feedstock from which advanced biofuels can be produced. Annex IX is under revision, with the aim to improve the feedstock list, trough the clarification of the feedstocks and the possible inclusion of new materials. For lignocellulosic feedstock, a “cascading principle” is being considered, i.e., if the feedstock is potentially useful for purposes other than energy applications, then, it might no longer be considered a residue. Therefore, it is suggested a careful assessment of the production processes to address this point. It is expected that by the end of this year the reviewing process will be finalised,

### **2. The introduction of the Fuel EU Maritime Initiative**

It aims to decarbonize the shipping industry by ramping up the use and production of renewable and low carbon maritime fuels through successively increasing GHG intensity reduction targets for ships. GHG emission factors of renewable biofuels meeting the sustainability and GHG saving criteria of RED II shall be determined according to the methodologies set out in RED II, whereas biofuels which do not meet those criteria shall be considered to have the same emission factors as the least favorable fossil fuel pathway for this type of fuel. The target group of this initiative are ship owners (>5000 gross tonnage). It has a pool compliance approach, in other words, the reduction is not expected for every ship, but for the fleet. It promotes a progressive reduction in GHG emissions, starting with 2 % by 2025, increasing to 75 % by 2050. In order to comply with this regulation, the Bio-HFO from IDEALFUEL will have to be certified according to the Directive (EU) 2018/2001. GHG emission reduction are the main focus to consider in this case; however, this is coupled with the capacity for blending of the Bio-HFO.

### **3. The revision of the Alternative Fuels Infrastructure Directive**

It aims to improve the development of the infrastructure needed for renewable and low carbon fuels. It is necessary to review what developments are being considered and how they can be applied for IDEALFUEL’s Bio-HFO infrastructure needs.

### **4. The gradual inclusion into the EU Emissions Trading System**

The EU Emission Trading System (EU-ETS) is a policy instrument used to make the reduction of GHG emissions cost-effective. Nowadays, it is implemented in all EU countries and EEA-EFTA states (Iceland,

Liechtenstein and Norway), covering around 40% of EU GHG emissions (European Commission, n.d.). It creates financial incentives to reduce emissions through a “cap and trade” system. The cap establishes a limit to the total amount of carbon Dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O) and perfluorocarbons (PFCs) that can be emitted. Over time this cap is going to be reduced (European Commission, n.d.).

Fit for 55 foresees the gradual inclusion of the maritime sector into the EU-ETS starting in 2023. A cap will be set to the maritime GHG emissions. The inclusion of maritime sector in the ETS means that the sector has to reduce the CO<sub>2</sub> emissions in 61% by 2030, compared to 2005 levels. The reduction is planned to be implemented gradually, 4.2% per year, and it will apply for ships above 5,000 gross tonnages of any flag. The cap will apply 100% for ships that travel within EU ports (intra-EU), and 50% for those whose travels start or end outside the EU (extra-EU). With this market-based measures in place, the shipping companies will have an obligation to purchase and surrender ETS emission allowances for their reported CO<sub>2</sub> emissions. The trading will be administered by a member state (McPhie & Rietdorf, 2021) .

## **5. The revision of the Energy Tax Directive**

Tax exemptions for conventional fossil fuels used in intra-EU shipping will be revised. This can indirectly affect the market position of IDEALFUEL’s Bio-HFO. The introduction of carbon taxes and a minimum tax level on fossil fuels in all EU countries will be beneficial to any advanced biofuel, especially for those that can offer higher CO<sub>2</sub> mitigation at a competitive price (McPhie & Rietdorf, 2021). Proposals from the aviation might impact the shipping sector, especially feedstocks availability due to competitive use for fuel production. Examples of such proposals are ETS for aviation, ETD tax rates for aviation and ReFuelEU Aviation (European Commission, 2021; European Commission, 2021)

### 3 Fuels in the Shipping sector

In addition to the legal arguments, already discussed in the previous section, the promising evolution of alternative fuels coping with marine necessities will also influence the future market size.

Heavy fuel oil (HFO) accounts for the major share of marine bunkering fuels. Figure 2 depicts the volume of bunker sales from the Port of Rotterdam. Although HFO represents the higher share of sales, it is expected a gradual reduction of HFO participation in fuel bunkering (Port of Rotterdam, 2021).

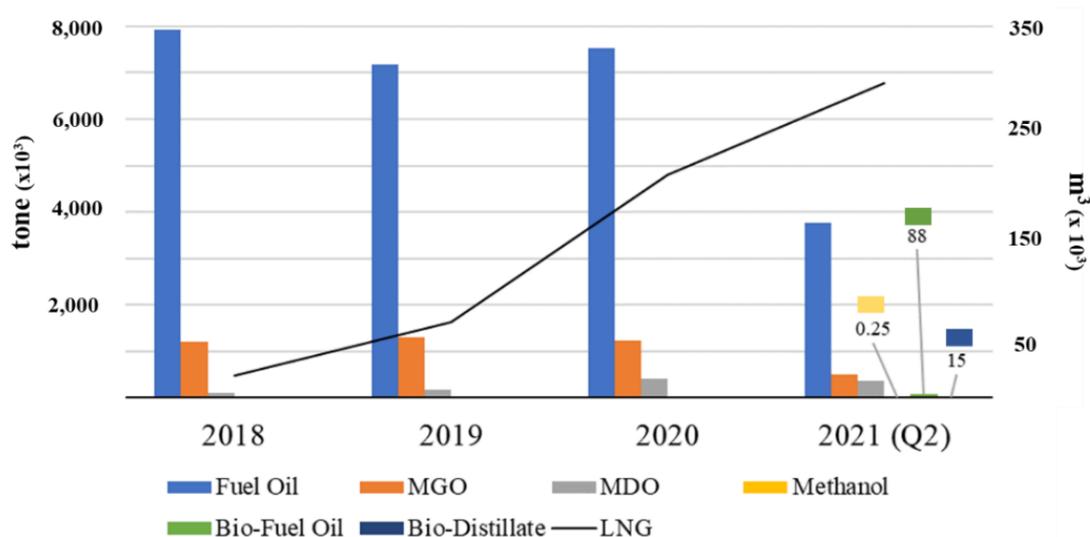


Figure 2. Port of Rotterdam Bunker Sales 2018-2021 (source: Port of Rotterdam, 2021)

The preference of a particular fuel will be influenced by three aspects, namely: i) fuel energy density; ii) compatibility with existing infrastructure and properties; iii) external factors, e.g., price, availability, and storage. Figure 3 depicts the energy density of different fuels for marine application, considering the tank weight needed. High energy density implies that the fuel requires less space, which allows better use of onboard space. The energy density also determines whether a fuel can be used in certain ship and ship operation. As can be observed some biofuels such as FAME, have lower energy density than HFO. Moreover, fuels like Ammonia or Hydrogen require special storage. The energy density and the storage system will also impact the bunker frequency (DNV GL, 2019).

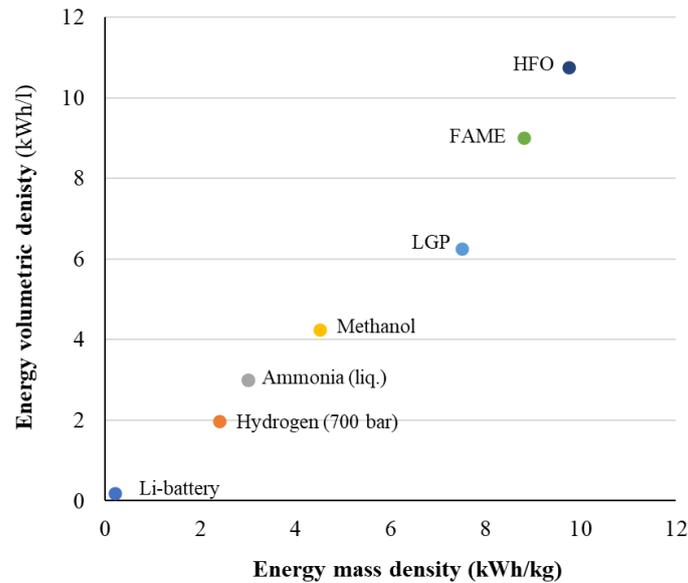


Figure 3. Energy density of several fuels considering tank weights and the low heating value (source: The Royal Society 2019)

\*LNG value will be similar to LPG

Although the current infrastructure is mostly designed for liquid fuels (at ambient temperatures), there are growing efforts towards gaseous (compressed or cooled) alternatives. Fuelling ships with gaseous alternatives has been considered a promising alternative by some, since fossil-based Liquefied Natural Gas (LNG) could be a readily cleaner option, in terms of CO<sub>x</sub>, SO<sub>x</sub> and NO<sub>x</sub> emissions in comparison to liquid fossil fuels. However, it has been observed that tuning the combustion engines for LNG and to reduce NO<sub>x</sub> emissions could lead to methane slip. Methane slip refers to the leakage of unburned methane due to incomplete combustion or fuel concealed in the crevices of the combustion chamber during compression (Pavlenko et al., 2020); which reduces its GHG emissions advantage as methane has a global warming potential greater than CO<sub>2</sub> (Houston, 2020). At the same time that the infrastructure could be used for improved technologies aiming higher decarbonisation, such hydrogen and ammonia (as alternative hydrogen carrier). Technologies to make these pathways commercially viable are still in development stages. The details of each alternative will be further discussed.

### 3.1 Marine Fossil Liquid Fuels

Marine fossil liquid fuels are classified between distillates and residual. They must comply with the specifications determined in ISO 8217, which specifies the requirements for fuels used in marine engines, boilers and stationary diesel engines. It sets seven categories of distillate and six for residual fuels (Oiltanking GmbH, n.d.). Distillate fuels encompass marine gas oil (MGO) and marine diesel oil (MDO). The first, and mostly traded as DMA. It is a light fraction of oil containing about 60 % of aromatics with low sulphur content (> 0.10 – 1.8 % w/w). It is usually used in auxiliary engines, small and medium ships, ships with frequent

varying speed and loads, and ships equipped with 4-stroke diesel engines. Low sulphur marine gas oil (LSMGO) contains less than 0.1 % w/w of sulphur and is used in ECA regions. Even lower sulphur content, up to 0.001% is found in ultra-low sulphur MGO, coping with the limits for inland use. MDO consists in a blend of distillates heavier than MGO, or a possible blend containing heavy fuel oil in low proportion. It has around 25 % w/w of aromatics, typically lower in cetane than MGO and with sulphur content between 0.3 and 2.0 % w/w. It is usually used in smaller ships operating in a constant speed and varying tonnage in 4-stroke engines. Residual Marine fuels are the heavy fraction of oil distillation and are available within a range of sulphur content and viscosities. Heavy Fuel Oil (HFO) is specified according to MARPOL definition as having either density and kinematic viscosity superior than 900 kg.m<sup>3</sup> (15 °C) and 180 mm<sup>2</sup>/s (50 °C), respectively. HFO is naturally rich in hydrocarbons with long molecular chain. It can be further refined by means of thermal and catalytic cracking, breaking long hydrocarbons into lighter molecules, thus decreasing the overall viscosity to meet desired specification. HFO can be used in blends with lighter fractions to meet specifications as needed. It is mostly used for large and slow ships working with 2-stroke engines, also used in 4-stroke engines though. Due to HFO's high viscosity, it requires heating, which increase the energy demand (Konur, 2021).

Residual marine fuels are named as RM, where R stands for residual and M for marine, for instance RME or RMG. They can be classified according to the viscosity as 180 and 380 mm<sup>2</sup>/s, RME 180 and RMG 380, respectively. Residual Fuels are also classified according with their sulphur content as: low sulphur fuel oil (LSFO) 1%, very-low sulfur fuel oil (VLSFO) 0.5%, and ultra-low sulfur fuel oil (ULSFO) 0.1 %. Based on the report from the Port of Rotterdam, the following market size for the different sulphur fuels was calculated. HSFO accounts for 30 - 40 % of total fuel oil sales, VLSFO ranges from 40 - 50 % and ULSFO accounts for 10-15 % of the sales (Port of Rotterdam, 2021).

Table 2 summarizes the key parameters for RME 180, RMG 380 and MGO (DMA) according to ISO 8217.

**Table 2. Marine gas oil (MGO) and marine diesel oil (MDO) specifications.**

Specification	Limit	MGO (DMA)	RME 180	RMG 380
Kinematic viscosity (centistoke)	Min - Max	2.00 - 6.00 at 40 °C	180 at 50 °C	380 at 50 °C
Density at 15 °C (kg/m <sup>3</sup> )	Max	890	991	991
Cetane number	Min	40	-	-
Sulphur (% w/w)	Max	1.5		3.5 %*
Flash Point (°C)	Min	60	60	60
Acid Number (mg KOH/g)	Max	0.5	2.5	2.5
Oxygen Stability (g/m <sup>3</sup> )	Max	25	-	-
Lubricity (µm)	Max	520	-	-
Pour Point (°C)	Max	-6 to 0	30	30
Carbon Residue – micro method (% w/w)	Max	0.3	18	18

\* Or as required in ECA zone

### 3.2 Alternative Fuels

The discussion about decarbonization put on debate the use of alternative energy carriers for marine use. Among them LNG, LPG, ammonia, hydrogen, methanol and biofuels can be listed. Below those fuels are further discussed.

**LNG** has been discussed as an early alternative to reduce direct emissions from engines, e.g. CO<sub>x</sub>, NO<sub>x</sub>, SO<sub>x</sub>. Product, transport infrastructure and engine technology are readily available. LNG consists of methane in its majority, with a small fraction of nitrogen, ethane, propane and butane. When cooled down to -160 °C, the gas is liquefied and reduces its volume, occupying 1/600<sup>th</sup> of its original space. The liquefaction process usually consumes 8% to 25% of the energy used to produce LNG (Balcombe et al., 2019; Oiltanking GmbH, n.d.). LNG can be used namely lean-burn spark ignition, 2 and 4 strokes low pressure dual-fuel, and high-pressure dual-fuel and gas turbine. Dual-fuel engines have been used for the past 40 years by LNG carriers. It was the first dedicated engine being constructed in 2000. Although LNG technology benefits by lower tank to wake emissions, 20% - 30 % reduction in comparison with liquid fossil fuels, the energy consumed during upstream has a negative impact on the overall emissions (Balcombe et al., 2019) Moreover, there is the downside of upstream methane leakage and downstream methane slip from LNG. When this slip emission are accounted in the life cycle (well-to-wake emissions), the emissions result higher than when using MGO, depending on the engine the increment could range from 17 % to 62% (Pavlenko et al., 2020)

**Bio-LNG** could be an alternative to fossil LNG, reducing overall emission to less than half compare with its fossil equivalent (Brynnolf et al., 2014). Bio-LNG is mostly produced from methanogenesis of organic material, from which a methane rich stream (up to 50 %) can be obtained. After upgrade, Bio-LNG can be used as a drop-in for fossil-based LNG. Nevertheless, for both, Bio and fossil LNG, methane slips during upstream and combustion might represent a threat to the environment and market use. Methane is, approximately, 30 times more impacting greenhouse gas than CO<sub>2</sub> (Myhre, G. et al., 2015).

**LPG** is a mixture of propane and butane in liquid form, which proportion is adapted according to the specifications. It is obtained as by-product of oil and gas extraction or during refining. It requires lower pressures for liquefaction than LNG, 8.4 bar and 1.2 bar for propane and butane, respectively (DNV GL, 2019). Similar to LNG, LPG requires tanks 2-3 fold times larger than liquid fossil-based equivalent. It can run in four kind of engines, namely 2-stroke diesel cycle and 4-stroke engines, lean burn Otto-cycle and gas turbine.

**Ammonia** is carbon free molecule which has been widely discussed as promising alternative for marine fuel. Among others, one could highlight the strengths of ammonia such as: i) it can be readily liquefied by compression (8 bar) at 20 °C or by cooling down (- 33 °C); ii) established production technology and infrastructure with a global production of 150 million tonnes in 2019; iii) narrow flammability; iv) can be used in internal combustion engines and fuel cells (Al-Aboosi et al., 2021). The first use of liquid ammonia as fuel

dates back to the 1940's, in buses. Although no critical issues from propulsion were reported, the use of ammonia in combustion engines has some disadvantages, e.g., low flame speed, high auto-ignition temperature, high heat of vaporization and toxicity (DNV GL, 2019). Alternatively, ammonia could be deployed in fuel cells; however, technology development is still necessary due to its immaturity. Ammonia is mostly produced through Haber-Bosch process, reacting  $N_2$  with  $H_2$  over a metal catalyst. Currently, 95% of the  $H_2$  used comes from fossil sources, mainly natural gas reforming, while  $N_2$  comes from energy intensive air separation production. This is a challenge for ammonia use that, if not surpassed, will limit the potential reduction of emissions. Green ammonia can be generated by using renewable energy, such as solar, during the production and by producing  $H_2$  from renewable sources, for instance, biogas or water. Blue ammonia is produced from fossil feedstock associated with carbons capture and storage technologies.

**Hydrogen**, is being considered as a promising fuel mainly due to its potential for emissions reduction and from the current experience on the chemical market. When used in adapted combustion engines it has an efficiency around 40 - 50%, whereas in fuel cell the efficiency is typically 50 - 60 %. The implementation of Hydrogen as fuel is still challenging due to technology constrains and present prohibitive costs (DNV GL, 2019). Storage and transport are mostly done as compressed hydrogen (250 – 700 bar), which requires a considerably input of energy. In addition to pressure, the small molecules of hydrogen also pose a challenge for the design of the storage and transport systems, which is usually translated to increased capital expenditures. Three types of hydrogen can be produced, depending on the process pathway. Grey hydrogen is produced via natural gas reforming. Blue hydrogen is produced by coupling carbon capture and storage (CCS) to the production of grey hydrogen. Finally, green hydrogen is produced from renewable feedstock associated with renewable energy, for instance water electrolysis powered with solar electricity. Hydrogen is, therefore, the alternative fuel which has the largest range on profile emissions.

**Methanol** is an alcohol with the lowest carbon/ hydrogen proportion among all liquid fuels. It is liquid at ambient temperatures; which facilitates its storage and transportation in comparison with the gaseous alternatives. Nevertheless, it has a lower energetic content and, therefore, requires larger fuel tanks to keep the same autonomy in comparison to regular liquid fossil fuels. The typical reduction in engine emissions is 99 % for  $SO_x$ , 60 %  $NO_x$ , 95 % PMs and 25 %  $CO_x$  (Balcombe et al., 2019). Methanol can be operated in a range of combustion engines, e.g, 2 and 4 strokes and Otto. In dual fuel engines methanol-air mixture is compressed and ignited by a diesel injection, or it is injected in a diesel pilot, similarly to gas-diesel system (Brynnolf et al., 2014). Methanol can also be used in fuel cells engines, but technology is still immature. The global market for methanol is about 100 million tons, primarily for chemical applications, placing it as one of the top five chemicals commodities (McCarney, 2020). The structure and knowledge already in place could benefit its eventual use in the transport sector. Comparably to the other alternative fuels, the production background of methanol has a significant impact on its total emissions. It can be produced from many sources, for

instance, natural gas reforming, catalytic hydrogenation of CO<sub>2</sub> waste streams or from biomass feedstock (Balcombe et al., 2019; Brynolf et al., 2014). Considering the natural gas path, the CO<sub>x</sub> emissions can be even superior than HFO, as shown in the emission section. On the other hand, the use of waste CO<sub>x</sub> streams will reduce the overall emission remarkably when considering the blue or green hydrogen alternatives. The tank to wake emissions might be assigned as biogenic CO<sub>x</sub> when the production comes from biomass, improving its environmental performance (Balcombe et al., 2019).

**Biofuels**, liquids, are among the alternatives here explored, the fuels with the greatest match to the available infrastructure. They can attain great decarbonization targets, at the same time that might be used as drop-in alternatives with little or no changes in the engine. Fuels such as straight vegetable oil (SVO), hydrotreated vegetal oil (HVO), fatty acid methyl ester (FAME) are available at commercial scale (Carvalho et al., 2021). Biofuels are benefited by a broader range of possible feedstocks, which favours local production, coping with energy security arguments. On the other hand, the debate about the eligibility of potential feedstocks, considering water and food security, is a hotspot discussion. To cope with the sustainable principle, residues and so-called waste-streams are always preferable while producing biofuels (IEA Bioenergy, 2017).

The use of advanced biofuel, produced from waste streams are crucial to cope with sustainability criteria, since production and expansion can be done without investment in new agricultural areas. Oil-based residues are suitable for the production of SVO, FAME and HVO. Currently, there is a limited offer of advanced biofuels in the market, specially produced from lignocellulosic residues. The exception relies on cellulosic ethanol, produced from crop residues. The heterogeneous and complex nature of the material and the diverse availability make the upgrade of lignocellulose into fuel a challenging task at commercial scale. There are different processing options for this kind of residues such as pyrolysis, hydrothermal liquefaction (HTL), gasification and bio digestion, as depicted in Fig. 4. These are at different stages of development though.

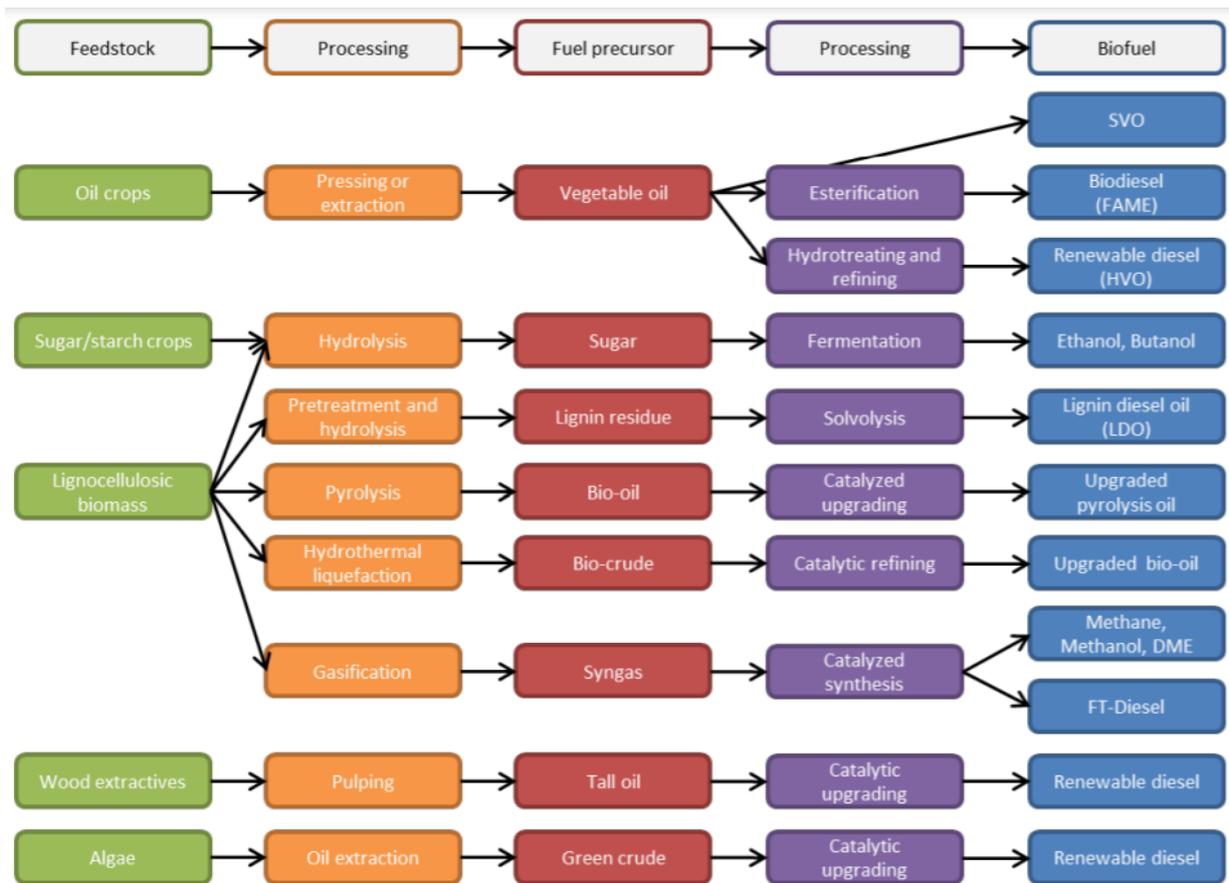


Figure 4. Overall flowchart for biofuel production starting from different feedstocks (source: IEA Bioenergy 2017).

### 3.3 Green House Gas Emissions

For marine fuels, IMO directives are the primary criteria on fuel selection, especially with regard to the sulphur content. They relate to the direct emissions coming from the engine, tracked back to fuel mass composition. GHG emissions, on the other hand, are accounted from the life cycle of the given fuel. Carbon dioxide equivalent (CO<sub>2</sub>eq) is the unit usually adopted on dealing with GHG emissions. It translates the impact of a group of molecules, e.g., CO<sub>x</sub>, NO<sub>x</sub>, SO<sub>x</sub> and methane (CH<sub>4</sub>), into a common unit expressed as a quantity of CO<sub>2</sub>. For example, one unit of CH<sub>4</sub> would account for approximately 30 units of CO<sub>2</sub>, based on their inherent intensity as greenhouse gas (Myhre, G. et al., 2015).

The life cycle emissions are quantified through the life cycle analysis (LCA) methodology, which considers the emissions from well-to-wake of the given fuel. Taking ammonia as an example, the LCA will consider the energy and material inputs consumed along the production chain, including emissions related to H<sub>2</sub> and N<sub>2</sub> production. LCA will also account emission for material disposal (The Royal Society, 2019).

The details of LCA are beyond the scope of this report, but it is valid to highlight that for each of the fuels addressed here, the LCA will consider the production particularities involved, including feedstock production, transport, conversion and combustion - fuels cells when applicable. Considering the variables

involved and the possible production methods, the range of GHG emissions and potential GHG reduction for each of the alternatives addressed in this report are depicted in Figure 5 and Table 2.

In RED II, article 31 and annexes V and VI deal with GHG emission quantification. Part C of annex V describes the calculation methodology, which follows the LCA principle, accounting emissions from raw material cultivation and extraction to end use.

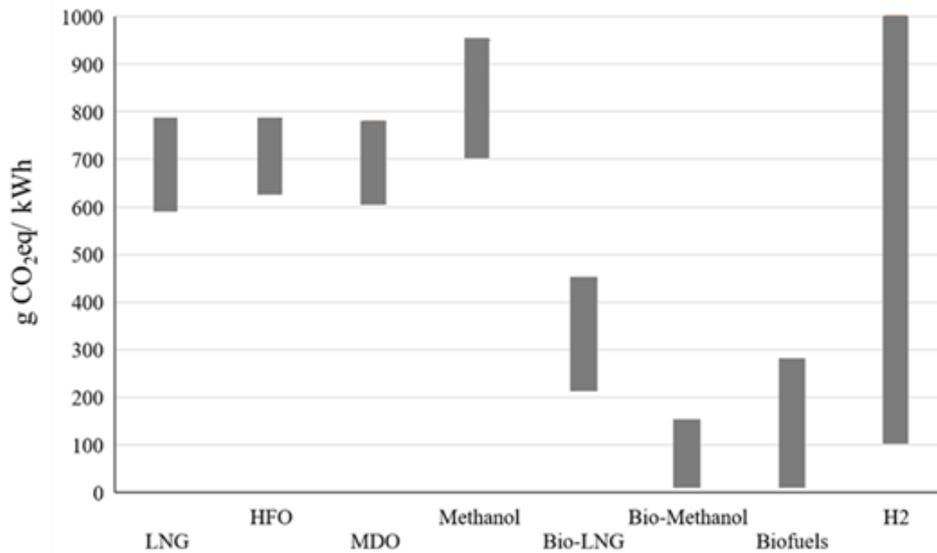


Figure 5. Emission profile for different fuels considering production background emissions (adapted from Balcombe 2018)

Table 2. Carbon savings from alternative fuels in comparison to HFO/MDO counterpart.

Fuel	Carbon Saving Potential (%)
LNG	- 5* to 25 %
Methanol	- 20* to 5 %
Hydrogen	- 20* to 100 %
Biofuels	25 to 100 %
Bio-LNG	39 to 65 %
Bio-Methanol	50 to 96 %

\*Negative values stand for higher emissions than fossil counterpart (Balcombe 2018).

On the context of IDEALFUEL project, it is important to assess the potential emission reductions and benchmark against the available fuels. Fuels with greater emission reduction, and lower costs will be preferred in the market. Tanzer and co-workers (2019) assessed the life cycle emissions of lignocellulose-based marine fuels from three conversions technologies: i) hydrothermal liquefaction with

hydrodeoxygenation; ii) fast pyrolysis with hydrodeoxygenation; iii) gasification followed by Fischer-Tropsch synthesis. They found that emissions reductions were within the range of 55 % to 133%. The feedstock production and transport emerged as emission hotspots, when the energetic matrix is mostly based on renewables. If fossil-based inputs are used, recycling is necessary. These will be the first points of comparison for the Bio-HFO (Tanzer et al., 2019).

### 3.4 Fuel Stability and Compatibility

Besides price and emissions, end users will consider the technical aspects of fuels use, which relates to fuel quality and engine compatibility (Panoutsou et al., 2021). Marine fuel stability is addressed by the method ISO 10307-2. The supplier has the responsibility to ensure the delivery of a stable fuel; whereas, best practices and tests to avoid the mixing of incompatible fuels are onboard responsibility. The fuel stability is measured from sedimentation test (ISO 10307-2), which evaluates the particulate formation from a single fuel or mixture. The spot test is a quick method (ASTM D4740) indicated to test the stability and compatibility of fuels with viscosity up to 50 cST at 100 °C. It consists in dropping a fuel or a blend on a test paper. Then assess the appearance of that based on a referred scale. To test the fuel compatibility the methods ASTM D7157, D7060 and D7112 can be applied (CIMAC, 2019). Fuel compatibility is a key aspect considering the adoption of alternative fuels. It brings cheaper solutions to market by means of blended products, at the same time, it does not limit bunkering fuel when there is not availability.

Apart from stability and compatibility, other criteria should be considered while addressing blend potentials. The sulphur content will determine the regions where fuels can be used and, therefore, its potential market segmentation. The flash point is another important property for end use, since it has a direct impact on fuel handling safety. In terms of engine performance, the density, heating value, cetane number and viscosity are key parameters to consider for the resulted blend. Density will affect the mass of injected fuel. Cetane number relates to the ignition properties. Viscosity will influence on the gas-liquid mixture homogenization and hydrostatic behaviour during injection while the heating value refers to the energy obtained during combustion (Panoutsou et al., 2021).

Table 3. Fuel and engine compatibility (adapted from Uslu, 2019).

Fuel	Drop-in	Engine's requirements
Pyrolysis oil	No	It is not compatible with the engine and fuel system. Adaptations are needed
Upgraded Pyrolysis oil	Yes	Similar characteristics to FT-Diesel and potentially be used for in-land shipping.
FT- Diesel	Yes	Need larger fuel tanks due to the lower volumetric energy density. Compatible with current vessel and port infrastructure.
HVO	Yes	Compatible with current marine diesel engines running on HFO, MDO, and MGO
(Bio) Methanol	No	Higher application potential for short-sea-shipping due to the lower energy density. Major changes in engine system are needed, including injection, ignition enhancer, fuelling system and storage.
Ethanol (lignocellulose base)	No	Similar requirements to methanol.

## 4 Future Market

The potential market for a fuel will depend on the market size and profile, legislation, competition and prices. In this section, each of these aspects are discussed, but legislation which has a dedicated section already discussed.

### 4.1 Market Size

Without specific policy in place, the future market for alternative marine fuels will be mostly governed by price on customer decision making. This assumption is also indicated by respondents of public consultation (Fig. 6), in which 87 % of respondents focused on the demand-side while addressing renewables uptake in the marine sector. In a business-as-usual scenario, the emission of maritime sector would rise 14% and 30% by 2030 and 2050, respectively, incompatible with the road map for carbon neutrality 2050.

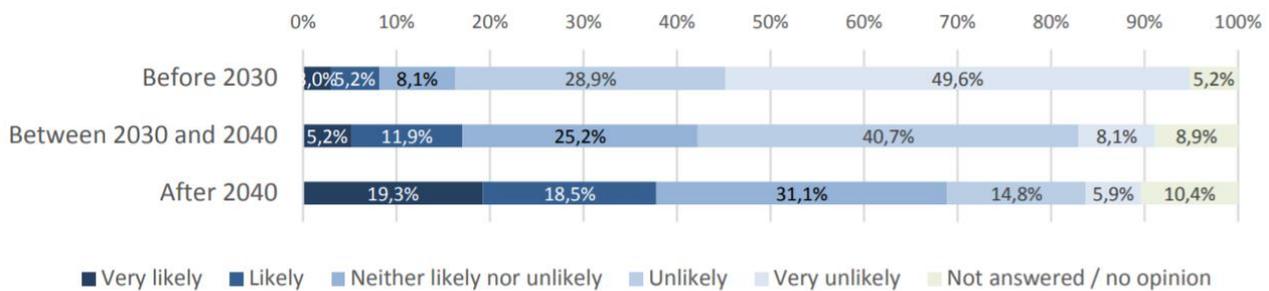


Figure 6. Public consultation: How likely is the uptake of renewable fuels in the marine sector without specific policy intervention? (Source: European Commission Proposal 2021 – Amending Directive 2009/16/EC)

Having said that, the future market of alternative fuels will be influenced, apart from price, by mandates and incentives. Mandates will guarantee a floor level for alternative fuels market size. Incentives will be translated into premium payment, benefiting the adoption of renewable fuels from a pricing perspective, most likely aligned to carbon equivalent metrics.

In 2018, IMO adopted the UN strategy for shipping GHG emissions with 3 main objectives: i) reduction in the energy intensity of ships; ii) international emission to decline by at least 40 % by 2030, pursuing efforts towards 70 % by 2050 (2008 base case); iii) total emissions to peak and decline as soon as possible, reducing total annual emissions at least by 50 % by 2050. Framed by these commitments, 3 different scenarios were assumed towards decarbonisation, two considering the uptake of hydrogen (H<sub>2</sub>) and one following the UN below 1.5 °C global warming potential, as depicted in Figure 7 (Prussi et al., 2021). Scenarios I, II and 1.5 °C consider a biofuel uptake of 37 %, 54 % and 54 %, respectively.

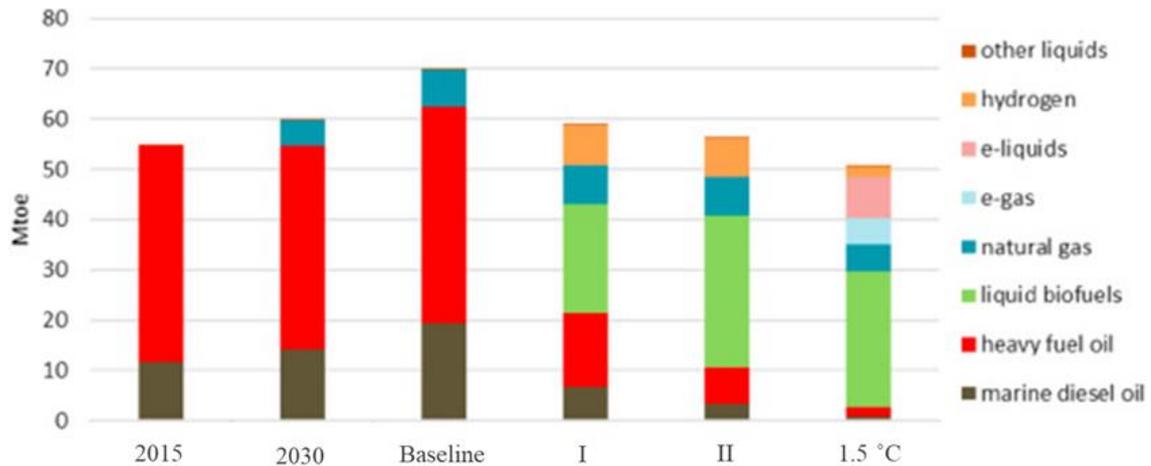


Figure 7. European Commission 2050 long-term scenarios for maritime fuel mix (source: Prussi et al., 2021)

## 4.2 Pricing

Price is usually the most impacting factor on costumers' decision making. Fossil fuels, on this regard, have enormous advantage on biofuels. The higher prices of biofuel are mostly attributed to its production and feedstock costs. Nevertheless, overall prices tend to decrease with time as a consequence of technology development and economy of scale (Brown et al., 2020). Feedstock availability is a crucial variable affecting biofuel production cost. For processes based on lignocellulosic residues, feedstock price accounts for 10 % to 20% of the production cost (Tanzer et al., 2019), whereas it might represent up to 60 % for other processes (Brown et al., 2020). While predicting the price of future biofuels can represent a challenging task, especially for post-COVID time, the currently scenario can provide valuable insights about product positioning. In figure 8, the price record for RMG 380, ULSFO, MGO and FAME are presented. As can be observed no clear tendencies can be concluded.

As mentioned before, fossil-based fuels have a substantial lower price than bio-based alternatives. On the other hand, bio-based fuel can benefit from the premium related to emissions reduction, whether GHG or sulfur. From the data is possible to infer the market premium for sulfur content by taking the spread between RMG 380 and ULSFO. The average price of HFO in the past 20 months is \$ 330/ ton, while an average of \$ 570 in found for ULSFO in the past 2 months, which it gives a spread of \$ 240/ ton. Considering the difference of 3.4 % in the sulfur content, linearly it suggests a premium of \$ 70/ ton for each percentage reduced in the sulfur concentration.

The Bio-HFO can also benefit from GHG mitigation. According to a survey conducted by the Emission Trade Association (IETA), the carbon price in the European market is expected to be around \$ 57/ ton between 2021 and 2025, and \$ 58.60/ ton between 2026 and 2030. In Table 4, the estimated benefit due to

decarbonization is presented in relation to one ton of HFO, assuming \$ 58/ ton and following RED II annex V, part C3.

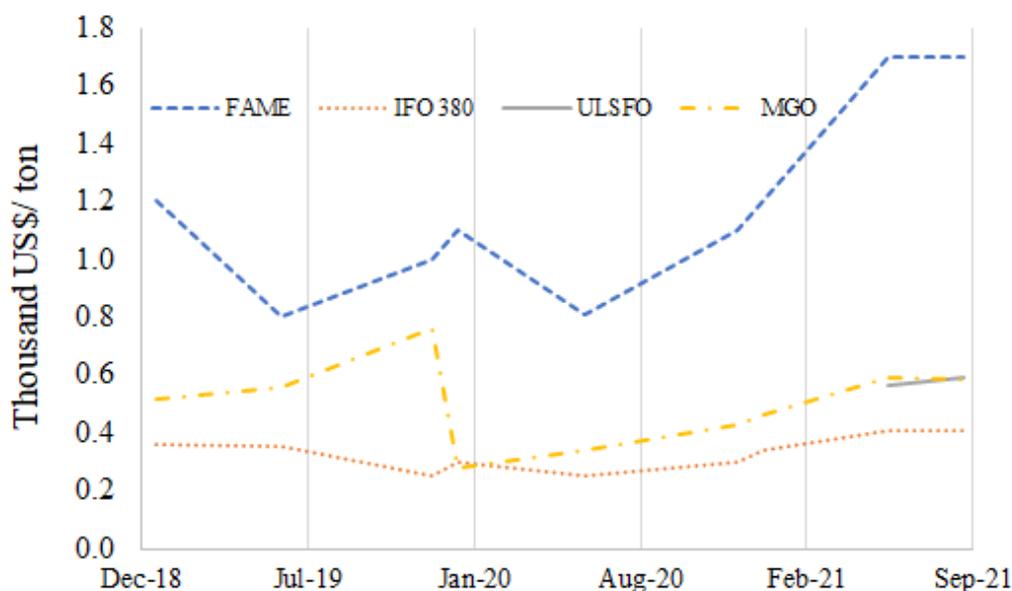


Figure 8. Price record of FAME, RMG (IFO) 380, ULSFO and MGO (source: Platts, Ship and Bunker).

Table 4. Decarbonization premium per ton of product in comparison to HFO, assuming equivalent densities and heat value and a carbon price of \$58/ton CO<sub>2eq</sub>.

Life Cycle GHG Reduction	Value of CO <sub>2eq</sub> reduction per ton of Bio-HFO
90 %	\$ 160
80 %	\$ 142
70 %	\$ 124
60 %	\$ 106
50 %	\$ 88
40 %	\$ 71

These assumptions however, might be considered for alternative fuels competing in the same segment of Bio-HFO. It is essential, therefore, to obtain a product which is compatible with fossil blending, making it even more attractive to end users. Another relevant aspect relates to the production costs, which can outnumber the premium benefit, for example, FAME (Figure 8). Based on the report of Oak Ridge National Laboratory (2018) funded by the US Department of Energy, a preliminary price for a marine fuel produced from lignocellulosic material, by means of hydrothermal liquefaction, would be around \$ 650/ ton.

### 4.3 Technology Maturity

Today, a few biofuels have a large production capacity to meet the volumes required in marine market. Their availability at large scale is one of the main factors that affect competitiveness, at the same time that it is dependent on the demand. Technological and market maturity is measure according to its readiness level (technology-TRL & commercial CRL) (Chiaramonti et al., 2021; Prussi et al., 2021). Many biofuels based on lignocellulose feedstock are being developed. It is important to realize that most of these lignocellulose-based fuels have a similar TRL to IDEALFUEL's Bio-HFO, and might represent potential competition.

**Table 5. Comparative of biofuels and their development status (source: Panoutsou et al., 2021; Prussi et al., 2021; Verbeek et al., 2020; Final, 2021)**

Feedstock	Conversion	Biofuel	Status
Waste oils stream: fat, used cooking oil, vegetable oils	Esterification / Hydrotreatment	FAME / HVO	Commercial
Sewage sludge, animal manure, agricultural residues	Biogas, methanogenesis	Biomethane, Bio-LNG	Commercial
Lignocellulose	Enzymatic saccharification and fermentation	Ethanol	TRL 8-9
	Enzymatic saccharification and fermentation	Methanol	TRL 6-7
	Hydrolysis and fermentation	Butanol	TRL 6-8
	Solvolyis	Lignin diesel oil (LDO)	TRL 6-7
Lignocellulose, solid and liquid industrial streams	Gasification and catalytic synthesis	Synthetic Fuel (Methanol, Ethanol, Long chain hydrocarbons)	TRL 6-7
Lignocellulose and Municipal solid waste.	Pyrolysis, liquefaction, hydrotreatment	Bio-oil, bio-crude	TRL 4-5
Wood extractives pulping	Catalytic upgrading	Renewable diesel	TRL 8-9
CO <sub>2</sub> from renewable systems	Reaction with renewable H <sub>2</sub>	Synthetic fuels	TRL 6-7

For the end user, besides pricing, it is important to consider the technical aspects of the solution. The use of advanced fuels will depend on the fuel quality, compatibility with the engine, GHG emission reduction and the infrastructure required (Panoutsou et al., 2021). Competition in this area include fuels like Pure Plant Oil (PPO) or Straight Vegetable Oil (SVO), Hydrotreated Vegetable Oil (HVO), Upgraded Pyrolysis Oil (UPO), biodiesel (FAME), and FT diesel.

The infrastructure needs to be considered, as some alternative fuels will require extra investment for infrastructure and retrofitting. Figure 9, illustrates the relationship of some alternative fuels with regard to infrastructure and compatibility with current fleet. There is the tendency of fleet operators to work with multiple-fuels, in order to cope with new legislatives requirements and minimize the future uncertainties.

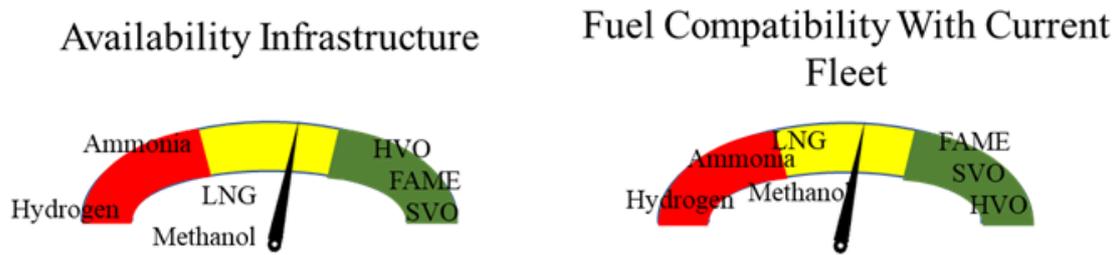


Figure 9. Infrastructure indicators for renewable fuels in EU. (Left) Indicates the availability according to the fuel, (right) indicates the compatibility with the current infrastructure according to the fuel (adapted from: Panoutsou et al., 2021).

## 4.1 Stakeholder mapping

A key task when assessing the market uptake of the Bio-HFO is to map out the key stakeholders, understanding motivations and plants. At this moment the potential stakeholders identified are feedstock providers, cellulose users and shipping owners (end users).

### 4.1.1 Feedstock Providers

Two types of feedstocks are being used for the production of the Bio-HFO, namely beech (hardwood) and residual pine (softwood). Beech trees are important timber sources in Europe, as well the most prevalent type in Central Europe. Therefore, increase attention should be paid to the market conditions and forecasting. Studies show that there will be a continuous expansion in the volumes of beech trees production favoured by higher temperatures and low precipitation. However, it is expected a decay in the southern European region due draughts caused by climate change. Among the competition, chine market is the principal consumer followed by European countries. Their application is mainly for the furniture and woodworking industries (Kozuch & Banaś, 2020).

Analysis of the market reveals seasonal fluctuations, which can affect the operation cost. Nevertheless, the seasonal variations can be considered of non-statistical significance, as the prices tend to stabilized in the long term (see fig 9) (Kozuch & Banaś, 2020). Long- and medium-term contracts are preferred rather spot negotiations to avoid seasonal variations or shortage, reflecting in more stable prices and liability on feedstock offer, especially considering the growing demand.

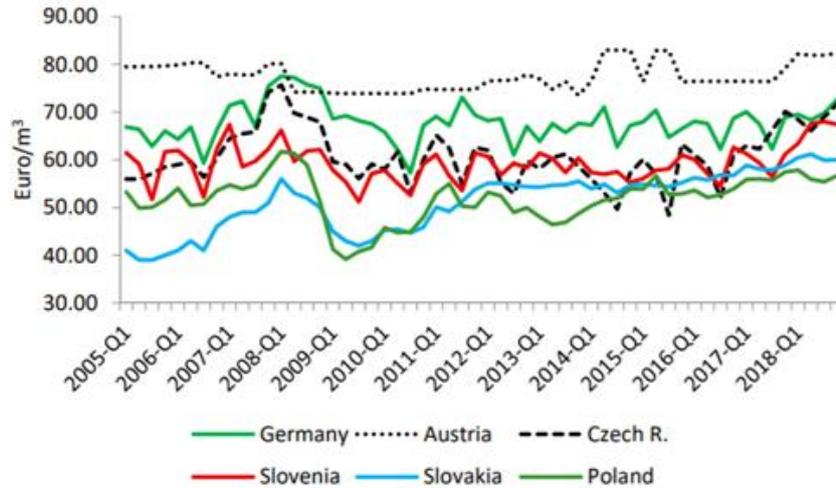


Figure 9. Nominal prices of beech roundwood in mayor European producer countries from 2005-2008 (source: Kozuch & Banaś, 2020)

Softwood production, particularly in central Europe and Sweden, is in continuous increase. The increased offer leads to lower price, as depicted in Figure 10, and higher local availability and, consequently, lower risk regarding waste softwood availability is foreseen.

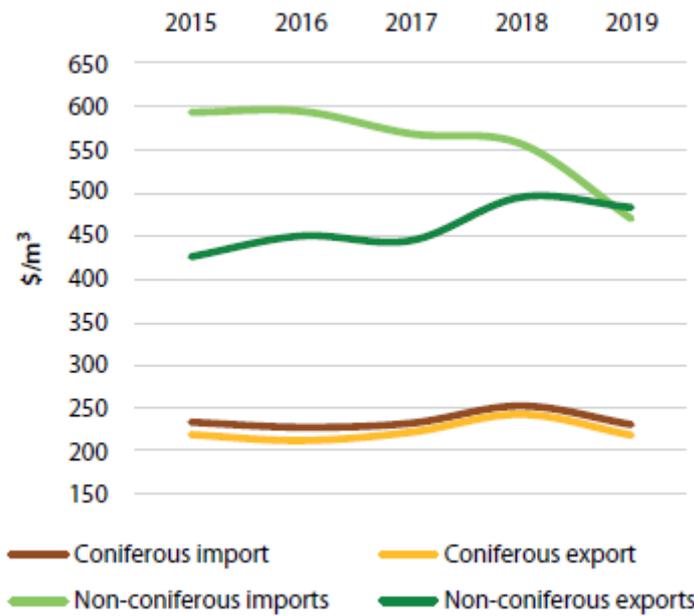


Figure 10. European softwood trade 2015-2019 (source: UNECE/FAO, 2020)

#### 4.1.2 Cellulose users

In order to produce the Bio-HFO, cellulose from woody biomass needs to be removed. However, due to possible changes in legislation, and in general to increase the sustainability overview of the project is necessary to ensure its (high) valorisation. Cellulose can have different market application such as pulp and

paper, or for the production of chemical. Pulp and paper are expected to remain the major shareholder followed by personal care industry (Fortune Business Insights, 2020). Using the environmental leverage of the higher sustainability of IDEALFUEL's process, can be of advantage to convince this uses of acquiring the cellulose. As alternative is the possibility of internal valorisation.

#### **4.1.3 Ship owners**

Lignin based fuels are not familiar to the shipping industry. Recently AP Moller-Maersk announced their interest in methanol-lignin blends to increase the energy density of methanol. Maersk has the intention to run ships of 2000 TEU on methanol (Team, 2021). However, the use of a lignin-based fuel in the shipping industry is yet to be proved, especially as a HFO equivalent. As a drop-in, the Bio-HFO is an attractive fuel, and demonstration project in large bunkering ports such as the Port of Rotterdam can influence public opinion significantly. The support of the port authorities can trigger demand. Once the demand increases, the systems and infrastructure needed will follow.

## 5 Conclusions and Recommendations

The success of IDEALFUEL's Bio-HFO, from a market perspective, will be influenced by 4 variables: i) legislation, mandates and incentives; ii) emission performance; iii) fuel compatibility and blend-ability; iv) production cost.

Current and future legislation propose a market environment favourable for biofuel uptake. With this regard it is imperative that the Bio-HFO complies with the norms and directives. To be considered an advanced fuel, the raw-material must be classified as waste. Noncompliance risks are lower if the lignin comes as a secondary (residue) stream within the process. In another words, the main purpose of feedstock acquisition is other than lignin valorisation. The fact that the residue (lignin rich) will be upgraded into a value-added product instead of being burned for heat purposes might be considered beneficial. Nevertheless, this aspect requires more than engineering and process design effort, since it is also ruled by political matters.

Emission performance will be translated into marketing advantages, whether by branding or premium benefit. The Bio-HFO must represent an effective alternative on SO<sub>x</sub>, GHG and NO<sub>x</sub> emissions, first two with higher impact on the pricing perspective. GHG emission will be very connected to feedstock classification as not-eligible for advanced biofuel production.

Fuel compatibility can represent a considerable restriction to Bio-HFO uptake. Generally speaking, wider the possible blending range is, more attractive will be product uptake. It is crucial to address the tests highlighted in section 3.4, and to target a final product with density, heat value, viscosity and flash point equivalent to fossil counter-part. The upgrade and product quality can pose a trade-off between production costs and market pricing, which must be considered when more information about the product is available.

Finally, the production cost. As just mentioned, it must be considered together with product specifications. Ideally, the Bio-HFO will benefit from the premium related to emissions, which should not be outnumbered by the production cost, as discussed in section 4.2. Fossil-based inputs, such as methanol, must be recycled to avoid extra GHG load from the production background, in order to keep GHG emissions as lower as possible. This should be carefully addressed in LCA studies.

The map of the alternative fuels considered in this report is presented in table 6. For each option a grade is given against specific and relevant criterion. Grades range from 1 to 5, 1 as very negative and 5 as very positive. Once the Bio-HFO has been carefully qualified, it can be assessed and compared with respect to these fuels, obtaining sharper market position.

Table 6. Marine fuels map

	Fossil			Renewable		
	HFO	LNG	Methanol	Biofuels	Ammonia	Hydrogen
<b>High Priority</b>						
Energy Density	5	3	3	5	3	2
Technological Maturity	5	4	3	5	2	2
Total Emissions	1	2	2	4-5	4	5
Energy Cost	5	5	3	3	1	1
Capital Cost	5	3-4	4	5	4	1
Bunkering Availability	5	4	2-3	3	2	1
Commercial Readiness	5	4	3	3-4	2	1
<b>Key Parameters</b>						
Flammability	5	4	4	5	2	2
Toxicity	3-4	4	3	5	1	5
Global production Capacity	5	4	4	2	2-3	3

## 6 Risk Register

Risk No.	What is the risk	Probability of risk occurrence <sup>1</sup>	Effect of risk <sup>1</sup>	Solutions to overcome the risk
1	Feedstock cannot be considered as waste according to the amendment of Red II.	2	1	Engage on lobbying discussion. Marketing of cellulose stream must be prioritized.
2	Lower regulation targets and carbon price .	3	2	Reduction in production cost must compensate a lower carbon price and decreased demand.
3	Low stability or compatibility with HFO or fossil-based fuels.	2	1	Process design working together with product testing.
4	Low oil prices	1	2	Minimize production costs and GHG emission to benefit from the carbon market.
5	Quicker market uptake of other lignocellulose-based fuels	2	1	Accelerate end user tests. Cost optimization.
6	Market tendency towards other alternative fuel: Methanol, LNG.	1	2	Accelerate end user tests. Cost optimization. Lobbying.

<sup>1)</sup> Probability risk will occur: 1 = high, 2 = medium, 3 = Low

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5	UNR	Uniresearch B.V.
6	WinGD	Winterthur Gas & Diesel AG
7		(Formerly SeaNRG, is now GOODFUELS #12)
8	TKMS	Thyssenkrupp Marine Systems GMBH
9	OWI	OWI – Science for Fuels gGmbH
10	CSIC	Consejo Superior De Investigaciones Cientificas
11	VARO	Varo Energy Netherlands BV
12	GOOD	GoodFuels B.V.



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