ADVANCEFUEL

Barriers to advanced liquid biofuels & renewable liquid fuels of non-biological origin

D1.1 Key barriers to advanced fuels-

Results of the stakeholder consultation

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Executive Summary

The overarching goal of the ADVANCEFUEL project is to facilitate the market roll-out of advanced liquid biofuels derived from lignocellulosic feedstocks and other liquid renewable fuels from non-biological origin (further jointly addressed as “RESfuels” in the report) in the transportation sector between 2020 and 2030, with an outlook on post-2030 impacts.

A policy driven demand versus supply dilemma

There is a politically agreed recast renewable energy directive that sets out the policy framework to 2030 which is expected to be adopted shortly. This recast directive introduces an overall renewable fuel obligation for the transport sector. By 2030, at least 14% of transport fuel energy demand should be met by renewable fuels. Within this target advanced biofuels produced mainly from wastes, residues, lignocellulosic and non-food cellulosic materials will need to supply at least 3,5% of transport fuel energy demand by 2030. The feedstocks that can be counted towards this sub-obligation are introduced in Part A, Annex IX of the recast directive. The part A list excludes biofuels produced from wastes such as used cooking oil and animal fats[1].

Currently, the majority of biofuels used in EU road transport consists of conventional biofuels based on food crops. The share of advanced biofuels was reported to be less than a quarter of the total EU biofuels mix in 2015[2], mostly driven by Sweden, the United Kingdom and Germany (EC. 2017). These biofuels consisted almost entirely of biofuels produced from used cooking oils and animal fats. The consumption of RESfuels (that are based on lignocellulosic feedstocks) are currently negligible and increasing the production and consumption of RESfuels will be challenging. The lignocellulosic feedstock based biofuels face many commercialization challenges and barriers. Unless these barriers are overcome, a smooth market roll out of these fuels seems difficult.

Objectives and the method

This report compiles the barriers to RESfuels based on the recent literature. It also includes the stakeholders’ views in regard to what extent they consider these barriers relevant. Their ranking is grouped as “extensive barrier”, “moderate barrier”, ”low barrier” and “no barrier”.

The main objective is to introduce the stakeholder validated and prioritised barriers so that the following work packages (WPs) can sharpen their focus in this project. The most critical barriers (referred to as extensive) will be analysed in detail and innovative solutions to overcome these barriers will be provided over the course of the ADVANCEFUEL project.

The questionnaire has been sent to around 100 stakeholders representing industry, research organisation & academia, agriculture and forestry sector experts and end-use sector experts (from road transport, maritime sectors and aviation). Furthermore, stakeholders are approached in different workshops and conferences and encouraged to contribute to this consultation.

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1 These feedstocks are included in part B of the recast Directive and biofuels derived from these are kept to maximum 1.7% of the transport fuel energy demand.

2 It is approximately 23% of the total EU biofuels mix in 2015, without multiple counting.

In total 31 reactions were received. Figure 1 presents the contribution of different stakeholders to the consultation. The majority of the participants were from the academia and research organisations. This is followed by the industrial stakeholders. The representation of the end-use sector was unfortunately very limited.

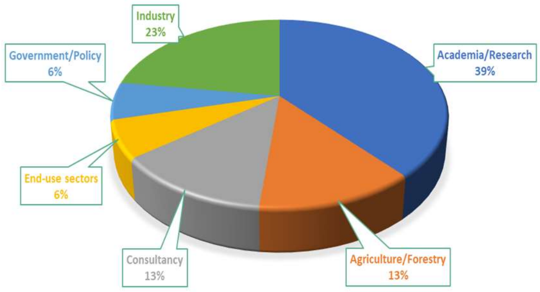

Figure 1 illustration of stakeholders participated to the consultation

Stakeholder consulted priority barriers

The stakeholders were requested to provide their feedback on different steps of the value chain, notably feedstock supply, conversion and end use. Table 1 recaps the top four barriers that were considered as extensive for each step by a large number of stakeholders.

The main concerns for the lignocellulosic feedstock supply relate to the regulatory and environmental issues. The lack of clarity on environmental constraints for lignocellulosic feedstocks and lack of harmonised regulation on residual biomass from farming practices, dedicated energy crops and also sustainable forest management are conceived as extensive barriers by a large number of stakeholders (~40% and higher). These may be partly explained by past experiences. Biofuels have been extensively scrutinised regarding their environmental sustainability. The environmental rules and regulations have been set but they mainly cover conventional feedstocks. There is a very limited focus when it comes to lignocellulosic feedstocks. The stakeholders also pointed out the high cost of feedstock as an extensive barrier. In fact, the single most important independent variable which would influence overall production cost of advanced biofuels is feedstock price (SGAB, 2017).

For the conversion step, the stakeholders state that RESfuels are driven by the policies and in the absence of dedicated policy support there will be no RESfuels produced. Equally important, the lack of long-term and stable policy support to provide stability and security for the industry (including pricing and regulation of (competing) fossil fuels) is mentioned as an extensive barrier. Investors expect policy support to be stable over a timeframe that is long enough to realize a return on investment. Difficulties related to access to project finance is also highlighted by more than 60% of the stakeholders that filled in the questionnaire. In general, the industry is considered to be a high risk investment, given past failures, high capital costs and reliance on policy support. Additionally, high cost of renewable hydrogen (H_2) production is mentioned as an extensive barrier for the future market uptake of RESfuels. This topic is mainly relevant for the pyrolysis case, where pyrolysis oil can be deoxygenated and (co-)fed to a catalytical cracking unit. Technical challenges such as difficulty in handling multiple processes or the low overall efficiency of the process are considered as moderate to low barrier by the majority of the stakeholders.

The extensive barriers related to the end-use sector are stated as the high production costs of RESfuels when compared with fossil fuels, subsidies provided to fossil fuels and the absence of structural mechanisms to bridge the financial gap between RESfuels and conventional fuels. Currently, the production cost of RESfuels, on average, is around 2.5 times higher than the conventional fossil comparator, and how far a dedicated quota obligation may push a complex and immature market is to be seen in the coming years. Relevant to the economics of RESfuels, manufacturers' unwillingness to change is stated as an important barrier.

The stakeholders mention mainly the high cost of CO_2 capture and the production capacity to capture CO_2 from the air, the cost of (renewable) electricity to produce H_2 and the high energy consumption of the regeneration process of CO_2 capture as the extensive barriers related to the RESfuels of non-biological origin.

Table 1 Summary of top four priority barriers based on the stakeholders reactions. Barriers are listed by their level of priority, starting with the highest priority in each step.

Type of barrier	Name of barrier
Lignocellulosic feedstock supply step	
Environmental	Lack of clarity about environmental constraints
Regulatory/ environmental	Lack of harmonised regulations on sustainable farming practices for residual biomass and dedicated energy crops
Economic	High cost of feedstock
Regulatory/ environmental	Lack of harmonised regulations on sustainable forest management
Conversion step	
Regulatory	Absence of dedicated policy support
Regulatory	Concerns on stability/security of the industry
Economic	Cost of renewable H_2 production
Economic	Access to project finance
End-use step	
Regulatory	Absence of structural mechanism to bridge the price gap between renewable and fossil-based fuels
Economic	High production cost of RESfuels
Regulatory/ economic	Fossil fuels still receiving subsidy
Economic	Manufacturers unwillingness to change
RES fuels of non-biological origin	
Economic	Cost of CO_2 capture systems
Technical	Production capacity of direct air capture
Economic	Cost of electricity
Technical	Energy consumption of the regeneration process of CO_2 capture

All above barriers stated by the majority of the stakeholders are important starting points to focus on and define solutions. However, this questionnaire is still susceptible to the usual short-comings questionnaires may face. We have kept the questionnaire short and simple (with mostly multiple choices) to increase the willingness to participate. This creates the risk that the stakeholders may have had different interpretations of the questions, resulting in subjective answers. Next to that, the majority of the responses have been from the stakeholders from research organisations and academia. The limited participation from the market (particularly end-use) can be seen as a risk, but given the objective status of research organisations and academia one can also consider this as a strength.

Contents

1. Introduction

1.1 Background

The overarching goal of the ADVANCEFUEL project is to facilitate the market roll-out of advanced liquid biofuels and other liquid renewable fuels (further jointly addressed as "RESfuels") in the transportation sector between 2020 and 2030, with an outlook on post-2030 impacts. It will do so by providing market stakeholders with new knowledge, a user-friendly set of tools with integrated calculators, standards, and recommendations to remove the most prominent barriers against their commercialization. More details can be found on www.advancefuel.eu**. This report is part of the Work Package 1 and refers to D1.1 Key barriers to advanced fuels.**

In recent years, the policy focus on renewable fuels has shifted from conventional biofuels to advanced biofuels. In 2015, the ILUC Directive (2015/1513) introduced an indicative target of 0.5% for advanced biofuels (EC 2015). The recent proposal for a recast of Renewable Energy Directive (REDII) (2016/0382) has further introduced an EU incorporation obligation to fuel suppliers for advanced biofuels and other biofuels and biogas produced from feedstock listed in Annex IX, from renewable liquid and gaseous transport fuels of non-biological origin, from waste-based fossil fuels[3] and from renewable electricity. While a wide range of biomass feedstocks are included in Part A of Annex IX, the majority of them are lignocellulosic feedstocks. According to the politically agreed recast directive, which is expected to be adopted shortly, the minimum share of energy from these fuels should be at least 14% of the total road and rail transport energy demand by 2030. Within this total share, the contribution of advanced biofuels and biogas produced from feedstock listed in part A of Annex IX shall be at least 3.5% of the total road and rail transport energy demand by 2030 and all biofuels produced form Annex IX shall be counted double (by energy content) to the set obligation.

Increasing the production and consumption of advanced biofuels produced from lignocellulosic feedstocks will be challenging. In 2015, the majority of biofuels used in EU road transport consisted of conventional biofuels based on food crops. The share of biofuels produced from wastes, residues, lignocellulosic and non-food cellulosic materials was reported as 23% of the total EU biofuels mix in 2015[4], mostly driven by Sweden, the United Kingdom and Germany (EC. 2017). These biofuels consisted almost entirely of biofuels produced from used cooking oils and animal fats. Consumption of lignocellulosic and non-food cellulosic feedstock-based biofuels were less than 1% of the total biofuel mix. The lignocellulosic feedstock based biofuels face many commercialization challenges and barriers. Unless these barriers are overcome, a smooth market roll out of these fuels will be difficult.

3 The November 2017 Council revision refers to this as recycled carbon fuels.

4 Without multiple counting.

1.2 Objectives

The ADVANCEFUEL project focuses on lignocellulosic feedstock based liquid biofuels and liquid renewable fuels from non-biological origin, further jointly addressed as "RESfuels". This report compiles the barriers to RESfuels that have been reported in recent literature. It also includes the stakeholders views in regard to how they rank these barriers. The report serves as input to work packages (WPs) 2-6. These WPs will analyse the barriers prioritised by stakeholders in detail and will develop possible solutions to overcome them.

1.3 Approach

First, a literature review is carried out to introduce the barriers that have been reported in recent literature. The information is collected from 52 sources and presented in the sections 3.2, 3.3, 3.4 and chapter 4.

This is followed by a questionnaire. Based on the barriers identified through literature review, an easy to fill in questionnaire was prepared and sent to various stakeholders and experts. The stakeholders were asked to evaluate the listed barriers. They could respond to the question with "no barrier", "low barrier", "moderate barrier", or "extensive barrier" as answers. The participants could also chose "no idea" or leave the question unanswered.

The questionnaire was sent to around 100 stakeholders and experts within the field of RESfuels. The survey was also accessible via the website of ADVANCEFUEL for 3 months.

This resulted in the response of 31 stakeholders from various sectors, which we categorized into 6 categories: academia/research, agriculture/forestry, consultancy, end-use sectors, government/policy, and industry. Figure 2 illustrates the distribution of stakeholders over the sectors. The results of this survey are depicted in the figures in chapters 3 and 4, and are discussed throughout the text in more detail.

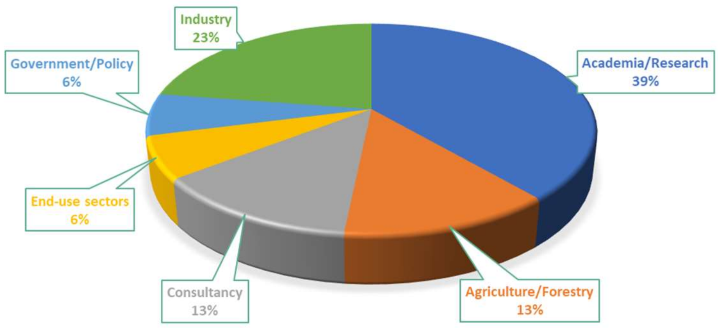

Figure 2. Sectors covered in the questionnaire by the stakeholders

1.4 Report structure

Chapter 2 introduces the current status of the lignocellulosic feedstock based biofuel industry in Europe. Existing and planned advanced biofuel plants in Europe are introduced.

Chapter 3 presents the main barriers identified through a comprehensive literature review and categorizes them as technical, economic, social or environmental constraints. These barriers are structured according to their specific location in the RESfuel value chain, i.e.:

- Lignocellulosic feedstock supply
- RESfuel conversion
- RESfuel distribution and end use.

Chapter 4 is dedicated to liquid renewable fuels from non-biological origins. This chapter introduces the possible production pathways and their technology readiness levels (TRL) and introduces the key challenges for these type of RESfuels.

Each section in chapter 3 and 4 also introduces the priority barriers defined through consultation and further elaborates on the reactions from the stakeholders.

2. Status of advanced biofuel plants

Existing and foreseen plants are either (biochemical) enzymatic fermentation plants (for ethanol production) or (thermochemical) routes towards diesel substitutes.

Advanced enzymatic fermentation of hemicellulose (e.g. bagasse, corn stover, straw) that produces second generation bioethanol is close to commercial application, while enzymatic fermentation of lignocellulose (e.g. wood) is less developed (IEA-RETD 2015). There are several industrial first-of-a-kind plants using agricultural residue and most of them are located in the US.

Figure 3 presents the total bioethanol production capacities in Europe, which are either in operation or idle, each plant at the TRL level of 6 or higher[5]. Among the plants, the only operational, first-of-a-kind demo plant is in Norway. This plant uses sulphite spent liquor from spruce wood pulping as feedstock, and there are plans to expand the production capacity of this plant. The other first-of-a kind demo plant is BETA Renewable's Crescentino in Italy. This has the largest lignocellulosic ethanol production capacity, at 6000 t per year. It was opened in 2013 and it ran on rice straw, wheat straw and giant reed. In 2017, unfortunately, Beta Renewables announced that it was closing this cellulosic refinery.[6] Earlier in 2016 Abengoa, left the sector due to bankruptcy and therefore the plants in Spain are also idle. Another unfortunate event for the sector has been the announcement that Dow DuPont was exiting the cellulosic biofuels business.

Clariant appears as a promising chemical company. They have a demo plant operational in Germany and have announced plans to build a cellulosic ethanol plant in Romania based on their Sunliquid process. They also have similar project plans in Slovakia (see Figure 4). Figure 4 shows that the planned projects are roughly six times the current capacity (when idle plants and the projects on hold are excluded).

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[5] Plants smaller than 100 t/year are not included.

[6] as parent company Mossi&Ghisolfi was filing for bankruptcy.

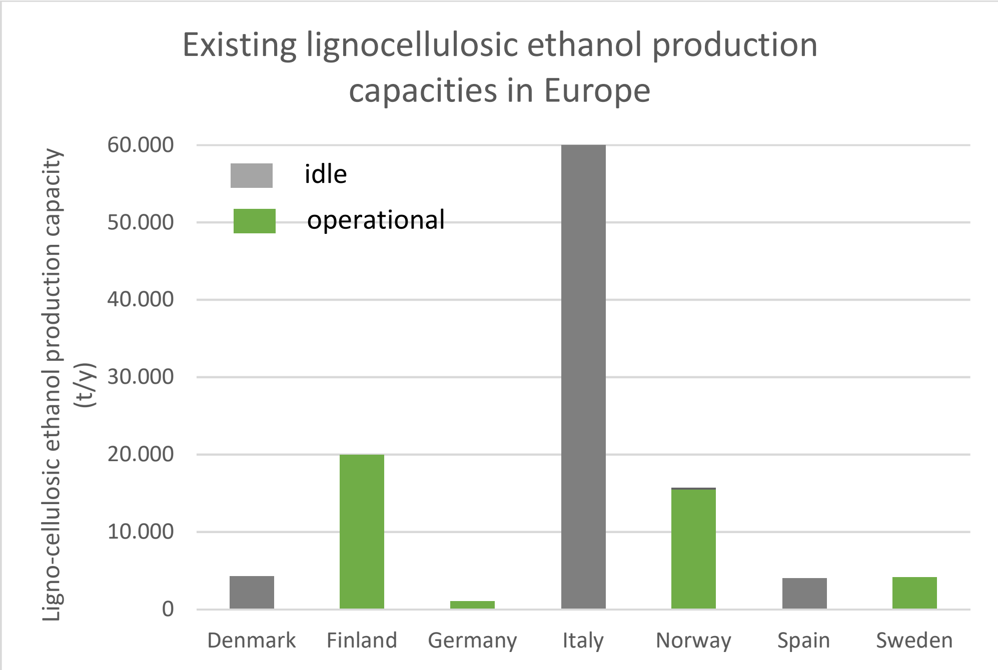

Figure 3 Existing lignocellulosic ethanol demonstration and first-of-a kind commercial plants in Europe (TRL 6 and above) (IEA Bioenergy, 2018)

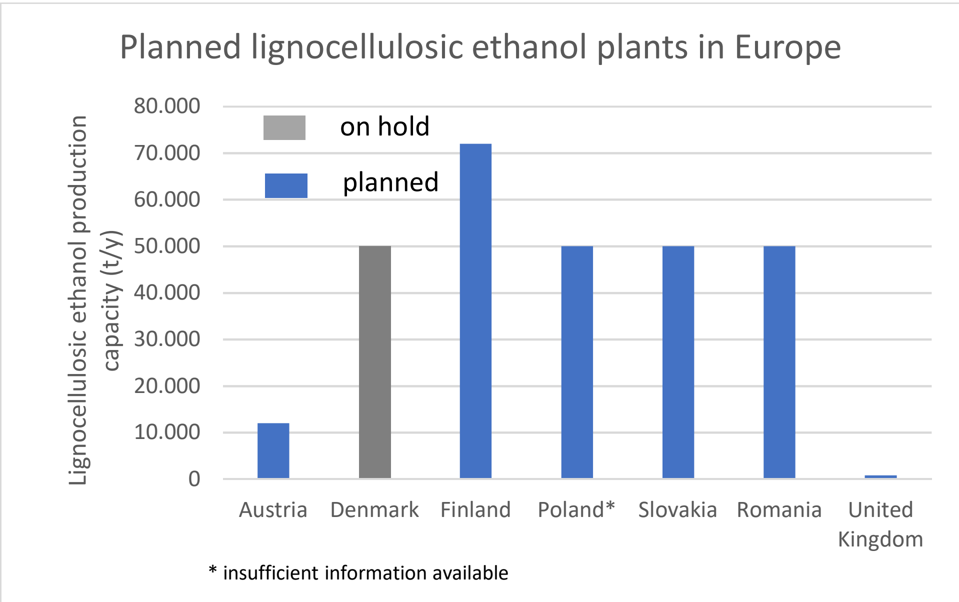

Figure 4 Production capacity of advanced bioethanol installations in the planning with a TRL 6 and higher(IEA Bioenergy 2018; RVO 2017, own research)

There is a diesel-type first-of-a kind commercial demo plant that is operational in Sweden. This plant uses tall oil as the primary feedstock and produces renewable diesel. UPM biofuels has also been producing renewable diesels on a commercial scale using crude tall oil since 2015. There is one project (BioTfueL) mentioned as operational since 2017 that uses lignocellulosic feedstocks such as straw as raw material and produces FT liquid in France (IEA, 2018). In this plant, biomass is first torrefied and then converted into syngas in a gasifier. The target year for full demonstration of this plant is mentioned as 2020.

Next to lignocellulosic ethanol and diesel, there are plans to produce other type of advanced biofuels. A commercial plant in Sweden (Varmlandsmetanol) is planned to use domestic forest residues and produce methanol. The methanol production has also been planned in the Netherlands by BioMCN, however, these plans are currently on hold. There is also a plan to produce butanol in the United Kingdom that uses wood chips.

Table 2 introduces the lignocellulos ethanol plants that are operational or idle and Table 3 presents the plans for lignocellulosic ethanol biofuel production in Europe. Finally, Table 4 presents the status of lignocellulosic diesel plants in Europe.

Table 2 List of bioethanol plants in operation in Europe or idle (with production capacities > 1000 t/year) (Biofuels Digest 2012; IEA Bioenergy 2018; RVO 2017)

Country	Company	Feedstock	Fuel	Production capacity [t/year]	Status
Denmark	Inbicon (DONG Energy)	Lignocellulosic - wheat straw	Ethanol	4300	Idle
Denmark	Inbicon	Lignocellulosic - wheat straw	Ethanol	4325	Idle
Finland	St1 Biofuels Oy	Green waste - Household and municipal waste	Ethanol	7000	Operation
Finland	St1 Etanolix	Lignocellulosic - Sawdust	Ethanol	7491	Operation
Finland	Chempolis Ltd.	Lignocellulosic - Non-wood and non-food lignocellulosic biomass such as straw, reed, empty fruit bunch, bagasse, corn stalks, wood residues	Ethanol	5029	Operation
France	Procethol 2G (Futurol)	Lignocellulosic - woody and agricultural by-products, residues, energy crops	Ethanol	2700	Operation
Germany	Clariant	Lignocellulosic - wheat straw	Ethanol	1000	Operation
Italy	Beta Renewables (joint venture of Mossi & Ghisolfi Chemtex division with TPG)	Lignocellulosic -	Ethanol	60000	Idle
Spain	Abengoa Bioenergy	Lignocellulosic - cereal straw (mostly barley and wheat)	Ethanol	5056	Idle
Sweden	North European Oil Trade Oy	organic residues and waste streams	Ethanol	4000	Operation

United Kingdom	TMO Renewables	Lignocellulosic - DDG, cassava stalk	Ethanol	3889	Operation

Table 3 List of bioethanol plants in the planning or construction process (capacities > 1000 t/year) (IEA Bioenergy 2018; RVO 2017)

Country	Company	Feedstock	Fuel	Production capacity [t/year]	Status
Denmark	Maabjerg Energy Concept Consortium	Lignocellulosic -	Ethanol	50000	On hold
Finland	Fibre EtOH	Lignocellulosic - Fibres from paper production	Ethanol	19444	Planned
Finland	Suomen Bioetanoli Oy	Lignocellulosic - Straw	Ethanol	72000	Planned
France	Abengoa Bioenergy	Lignocellulosic - Gasified corn harvest and forest residues	Ethanol	62222	Planned
Poland	SEKAB	Lignocellulosic - Wheat straw and corn stover	Ethanol	50000	Planned
Slovakia	Energochemica SE	Lignocellulosic - wheat straw and other biomasses such as switch-grass, rapeseed straw and corn stover	Ethanol	55000	Under construction
Spain	Abengoa Bioenergy	Wastes - Municipal solid waste	Ethanol	1190	On hold
Sweden	Varmlandsmetanol	Lignocellulosic - domestic forest residues	Other	100000	On hold
Sweden	Sala Heby Energi	Lignocellulosic - Wood	Ethanol	3889	Planned
Sweden	Härjedalens Miljöbränsle AB, National Bio Energy Co. Ltd., Dragon Power Co. Ltd.	Lignocellulosic - Wood	Ethanol	2956	Planned
Macedonia	Ethanol Europe Renewables	Lignocellulosics -	Ethanol	77778	On hold
Italy	Beta Renewables	Lignocellulosics - Green waste	Ethanol	77778	On hold

Table 4 Status of biodiesel plants in Europe (with TRL≥6)

Country	Company	Feedstock	Fuel	Production capacity [t/year]	Status
France	Total BioTfueL demo	Straw, forest waste, dedicated energy crops	Diesel	200000[7]	Operational since 2017, however, full scale demonstration is considered in 2020
Finland	UPM	Tall oil	Diesel	100000	Operational
Sweden	Preem Petrol	Tall oil	Diesel	20000	Operational

[7] Envisaged for an industrial scale plant

3. Barriers to RESfuels from lignocellulosic feedstocks

3.1 Policy context

The market demand for biofuels has been driven by EU policies and their transpositions into national policies. The EU Renewable energy directive, introduced in 2009, mandated EU member states (MSs) to supply at least 10% of their transport fuel energy demand from renewable sources by 2020. This resulted in increased production and consumption of biofuels. However, the commercialisation of advanced renewable fuels has been slow. There were hardly any investments in biofuels in 2013 – 2015 (both conventional and advanced) (IRENA, 2016).

Past experiences have shown that:

- Dedicated targets and incentives to advanced fuels will be essential for innovative technologies with high risks and high capital expenditures.
- Only long-term policy support will be able to create sufficient investor confidence in investing in these technologies.
- In addition, low oil prices have been a major barrier to the competitiveness of the biofuel industry.

The recast renewable energy directive addresses the first of the above concerns by introducing a dedicated sub-target for advanced biofuels. It is questionable, however, whether the second point is sufficiently covered, as the recast directive contains a review moment by 2025, in which the market perspective for advanced biofuels can still change significantly. As for the third point, this will act as a barrier until carbon emissions or the fossil fuels are priced sufficiently high (either as a fuel tax, some other additional fuel cost or other cost associated with fossil-fuel powered vehicles (Johnsson 2018).

Sustainability concerns have been a major show stopper to conventional biofuels. Though, sustainability corners are not identified as show stoppers to advanced biofuel, past experiences have shown that a lack of comprehensive sustainability coverage and deficiencies of sustainability verifications will affect public confidence in policy design and put the further deployment of biofuels at risk. One example of sustainability concern is the discussion on Indirect Land Use Change (ILUC), and how this should be taken into account in policy. This illustrates that all relevant sustainability concerns should also be taken into account when developing advanced RESfuels.

The recast directive introduces a list of feedstocks to be used for advanced biofuels and it also presents a 70% greenhouse gas (GHG) emission reduction threshold for advanced RESfuels. The GHG emission calculation formula, however, excludes indirect land use emissions, assuming that the list introduced has zero indirect emissions. This assumption may result in continued debate in the coming years and affect public confidence[8].

Other barriers related to feedstock supply, the conversion technologies and end-use are detailed in the following sections.

3.2 Feedstock supply

Stakeholders identify the most crucial barriers related to feedstock supply as:

- *lack of clarity about environmental constraints*
- *lack of harmonized regulations on sustainable farming practices for residual biomass and dedicated energy crops*
- *high cost of feedstock*
- *lack of harmonised regulations on sustainable forest management.*

Overview of the barriers

Biomass feedstock supply includes biomass production and harvesting, storage and transportation. The focus lies on the lignocellulosic feedstocks to produce liquid advanced biofuels.

There is no simple and straightforward categorization of the barriers relevant to the feedstock supply step. They are mostly interlinked with each other. Still, a simplified categorization of barriers related to feedstock supply is presented in Table 5 and described in the following text.

Table 5 Barriers related to feedstock supply (based on the literature review)

Category	Barrier description
Technical	Difficulties in mobilising various feedstocks, from remote regions (i.e. The absence of a well-established logistic infrastructure; logistical barriers to harvesting, storage and transporting biomass feedstocks).
	Constraints relating to the quality, consistency, and homogeneity of feedstocks, and a lack of specifications and standards.
	Technical uncertainties regarding input required to turn marginal land types to productive and economically attractive systems for innovative cropping.
Economic	Competing uses (demand from various other sectors) result in higher feedstock prices.
	High pre-treatment storage and transportation costs (high cost of some feedstock pre-treatments and the low bulk densities of most

8 As an example, a recent publication states that ethanol production from molasses (a feedstock included in part B list of Annex IX) would not meet the 70% GHG reduction threshold of the EC's proposed REDII regulation, if the indirect emissions are also accounted for.

Category	Barrier description
	Lignocellulosic materials make them uneconomical to pre-treat, store and transport).
	Lack of market transparency across regions (no price discovery process for feedstocks like agricultural residues or wastes).
	High cost of determining the quality of feedstock for biofuels and the high cost of quality information in general.
	Unavailability of investments necessary for feedstock harvesting (for example, specialized harvesting equipment).
	Scarce readiness of farmers to assume economic risks in case of perennial crops, which do not bring an income each year.
	The lack of (and uncertainty in) profitability of dedicated energy crops in relation to current investments for fertilisation and weed control.
Social	Lack of knowledge among farmers and forest owners in many EU countries and difficulty for farmers and forest owners to adapt to new management practices.
	Agricultural feedstock residue sector is not structured (non-existence of agricultural residue sector associations), lack of communication between stakeholders.
	Lack of information from farm and agricultural organizations about new crops such as perennial grasses (e.g. Miscanthus) and short rotation coppice plantations (e.g. Willow, poplar, etc.).
	Cultural barriers to introducing new crops into a monoculture landscape.
	Farm characteristics (small farm holdings, etc.) And other demographic factors (i.e. Aging farming population) in farmer willingness to enter new markets and grow new crops.
	Importance of sustainable crop-based biofuels for the generation of socio-economic benefits in rural areas is underestimated.
Environmental	Lack of clarity about land availability and environmental constraints for non-food energy crops
Regulatory	Lack of harmonised regulations on sustainable farming practices for both residual biomass and dedicated energy crops.
	Lack of harmonised regulations on sustainable forest management.

There have been a number of studies (Biomass Policies, Biomass Futures, S2Biom, etc) concluding that Europe holds a significant biomass potential and the bioenergy targets set by the member states for 2020 and 2030 were in reach. Yet, in practice, mobilising and utilizing these potentials in full scale can be challenging, particularly when it comes to wastes and residues. There are habits and existing practices which can be difficult to change.

Some of the existing practices are as follows:

- In Spain and Italy the most common practice is to burn pruning residues directly on the field. In France, Greece, Slovenia, Netherlands, Germany, Slovakia and Poland the most common practice is the shredding of residues and leaving them on and/or incorporating them into the soil (Elbersen et al. 2014).
- Agricultural and forestry residues are left on soil to protect the soil's organic carbon. While a part of residues should be left on the soil for soil protection and the sustaining of the soil's organic carbon, residues may cause pollution to the soil and underground water when all/more than necessary is left on the ground. It is difficult to change the habits and existing well-rooted farming practices, e.g. burning or leaving agro-prunings on the fields.
- Many farmers that currently cut and incorporate their straw into soil may not be willing to bale straw for bioenergy purposes.

Particularly in Austria and Finland, forest residue feedstock mobilisation is well structured and developed. One of the main success factors for this situation is stated as the existence of a well-structured and developed sector, and the existence of forest management associations that assist the private forest owners. The agricultural feedstock residue sector, different than the forestry sector, is not structured. There is no lobby group to defend its interests or to develop communication on agro-biomass as is taking place with wood and other energy sources. Agricultural biomass thus still remains under-developed. Moreover, there is a lack of communication between stakeholders dealing with agricultural biomass (Dzene et al. 2017).

The absence of a well-established logistic infrastructure, which would allow for low-cost and efficient transport of these feedstocks, hampers biomass mobilisation (Dzene et al. 2017; Elbersen et al. 2014). The logistics to collect the feedstock both often severely limit the amount of biomass that can be supplied and drive up prices. Next to that, the supply of the biomass feedstock often suffers from the seasonal nature of the production (especially agricultural residues and energy crops). The discontinuous supply of biomass means that storage of large volumes of feedstock is necessary, which can add to investment costs and feedstock degradation during storage. Additionally, the high cost of some feedstock pre-treatments and the low bulk densities of most lignocellulosic materials make them uneconomical to pre-treat or to transport to centralized facilities for processing.

Securing feedstock supply with reasonable prices represents a necessary condition for advanced biofuel technologies, particularly when economies of scale are considered. This is particularly important for the non-traditional biomass feedstocks (such as agricultural residues, or wastes). On the one hand, investors in a cellulosic biofuel refinery might be unwilling to invest in new or expanded capacity unless they are certain about the quantity, quality and price of feedstock available to the refinery. Feedstock producers, on the other hand, would be unlikely to make the investments necessary for feedstock harvesting (for example, specialized harvesting equipment) without the assurance of a long-term buyer commitment (Dzene et al. 2017; National Research Council 2011).

So far, there is no price discovery process for feedstocks like agricultural residues or wastes, which adds to uncertainties for investors. Given the high cost of transportation and/or pre-treatment that is likely to exist for such feedstocks, the geographic regions over which such feedstock is traded are likely to be restricted (Bentsen et al. 2017). A limited number of biorefineries is likely to buy their feedstocks from a specific, nearby region. Thus, given the small number of buyers in the region, it is unlikely that the price variations and price information will be communicated across regions. The lack of market transparency and stability (fluctuations in feedstock prices) can become an important barrier for the advanced biofuels sector (National Research Council 2011).

Any uncertainty related to the quality of feedstock (for example, ash content, moisture content) will result in uncertainty regarding the value of that feedstock. If the cost of evaluating feedstock quality is high, this quality uncertainty would be reflected in the price of the feedstocks. As a consequence, the expansion of the cellulosic biofuel industry is likely to face a barrier in the high cost of determining the quality of feedstock for biofuels and the high cost of quality information in the pricing process (National Research Council 2011).

Relevant to the above points, a lack of specifications and standards related to the quality, consistency, and homogeneity of feedstock, may become a barrier as these may impact plant performance and guarantees.

Competing uses of biomass feedstock have also been indicated as a barrier to bioenergy sector in general. Next to demands from various sectors high demand and possibly higher buying capacity from power and heat sectors may make it difficult to use the lignocellulosic feedstocks for advanced biofuels.

Barriers related to innovative practices

Agriculture is a sector where both traditional and inherent practices are implemented and it is not easy to shift towards more innovative practices (when not directly linked to farmers usual activities) and innovative cropping schemes as needed for the production of dedicated energy crops:

- To date most farmers hesitate to produce perennials for long term periods as they are used to reacting to market developments on a yearly basis. This is accompanied by the uncertainty in the profitability of dedicated energy crops in relation to current investments.
- The importance of considering farm characteristics and demographic factors in farmers' willingness to enter new markets and grow new crops. Farmers who have higher off-farm income, higher education levels, and are younger are more willing to convert some of their land to switchgrass production. Farmers with higher net farm income per hectare are less likely to convert a large amount of land, indicating the opportunity cost of planting switchgrass (Jensen et al. 2007).
- The reluctance to convert land from traditional row crops to for instance a switchgrass crop is projected to be hindered by the volatility of biofuel prices and the costly reversibility of investment in a switchgrass crop (Song et al. 2011).
- Reviews with farmers revealed that farmers were sceptical regarding potential economic benefits of switchgrass. Their experiences with the switchgrass projects indicated that there were many technological, economic, and logistical barriers yet to be overcome before the biofuel industry could develop further (National Research Council 2011).
- Information about growing and harvesting lignocellulosic feedstocks and their market opportunities is not well known to the owners and producers. Sometimes cultural barriers exist preventing the introduction of new crops into a monocultural landscape. The owners/producers are not likely to grow or harvest the necessary amount of feedstock unless they receive (at the gate) a certain amount of money (this is particularly relevant for growing dedicated energy crops). Especially if there exists a competition for the feedstock with other sectors who are willing to pay more.

- Lack of clarity about the land availability and environmental constraints for non-food energy crops. Non-food energy crops have major potential but they may compete for land with other crops as producing those feedstocks on fertile lands will be much more profitable than producing them on abandoned and marginal lands.
- Cultivation of dedicated crops for advanced biofuels is suggested on marginal and low quality land, but, there are still many technical uncertainties about input required to turn such land types to productive and economically attractive systems.
- Despite the fact that lignocellulosic biomass cultivation entails a lot of benefits, the farmer does not get paid for the provision of ecosystem services (Porter, et al., 2009).
- In terms of the implementation of short rotation coppices (SRC) the identified obstacles are that EU subsidies focus mainly on the implementing rather than the maintenance costs (Keutmann,et al., 2016).
- In some European countries, majority of agricultural land is rented. Landlord can influence farmers' decision regarding their crop choice and often they are not in favour of crops which are on the field for longer time periods. Regarding Short rotations coppices (SRC), leasing contracts are often too short, thus SRC can only be implemented on owned land (Keutmann et al., 2016).
- Harmonisation of quality and traceability aspects: Different actors are not aware of the importance regarding biomass quality and how these aspect might affect the success of the entire supply chain (CIRCE, 2016).
- Lack of adequate and appropriate harvesting machineries and costly maintenance activities (Borremans et al., 2018; SLU, 2016).
- Operational costs of pruning as a feedstock for bioenergy account for 73%, while investment costs only account for 27%. Thus, more focus should be drawn on logistic operation and management (SLU, 2016)

Stakeholder consultation

The stakeholders were requested to evaluate to what extent they consider the above listed topics as barriers to the market uptake of RESfuels. In total 25 reactions have been received and illustrated in Figure 5. It is interesting to see that the stakeholders highlight a "**lack of clarity about environmental constraints**" as an extensive barrier even though RESfuels are considered to reduce or even avoid negative environmental pressure compared to food crop-based biofuels. Past experiences and sustainability discussions have nearly stalled the conventional biofuels sector, and apparently stakeholders have similar concerns regarding the new emerging industry. **"Lack of harmonized regulations on sustainable farming practices for residual biomass and dedicated energy crops and sustainable forest management**" have also been considered as an extensive barrier by an equal amount of stakeholders. Currently, use of (ligno)cellulosic feedstock to produce biofuels is insignificant. There are a few first-of-a-kind commercial and a number of demonstration plants that use agricultural residues to produce RESfuels (lignocellulosic ethanol). Use of dedicated energy crops to produce biofuels is non-existent. When the market uptake of such biofuels start increasing these two topics will become extremely important and unless they are addressed well the RESfuel sector may also be negatively impacted. For instance, it is widely acknowledged in sustainable farming that a fraction of residue should remain on the field to reduce erosion and protect soil organic carbon as well as nutrients. In addition, a fraction of residues is currently collected and serves to other purposes, mainly as animal bedding. There is, however, no harmonised regulation on these aspects. This will make it difficult to monitor such sustainability concerns. The Renewable Energy Directive

(2009) had a very limited definition of sustainability criteria for biofuels produced from dedicated energy crops at the EU level[9]. These two challenges are highlighted as extensive by around 40% of the experts who participated in the consultation.

The next extensive barrier pointed out by the stakeholders is the high **"cost of feedstock**", 38% of the participants mentioned this as an extensive barrier. In fact, the single most important independent variable which would influence the overall production cost is feedstock price (SGAB, 2017).

Among the introduced barriers, only two of them are seen as either low barrier or not as barrier by the majority of the stakeholders (light and dark green areas in the figure below). These are obstacles related to the "habits of current agricultural practices" and the "investments required for feedstock harvesting".

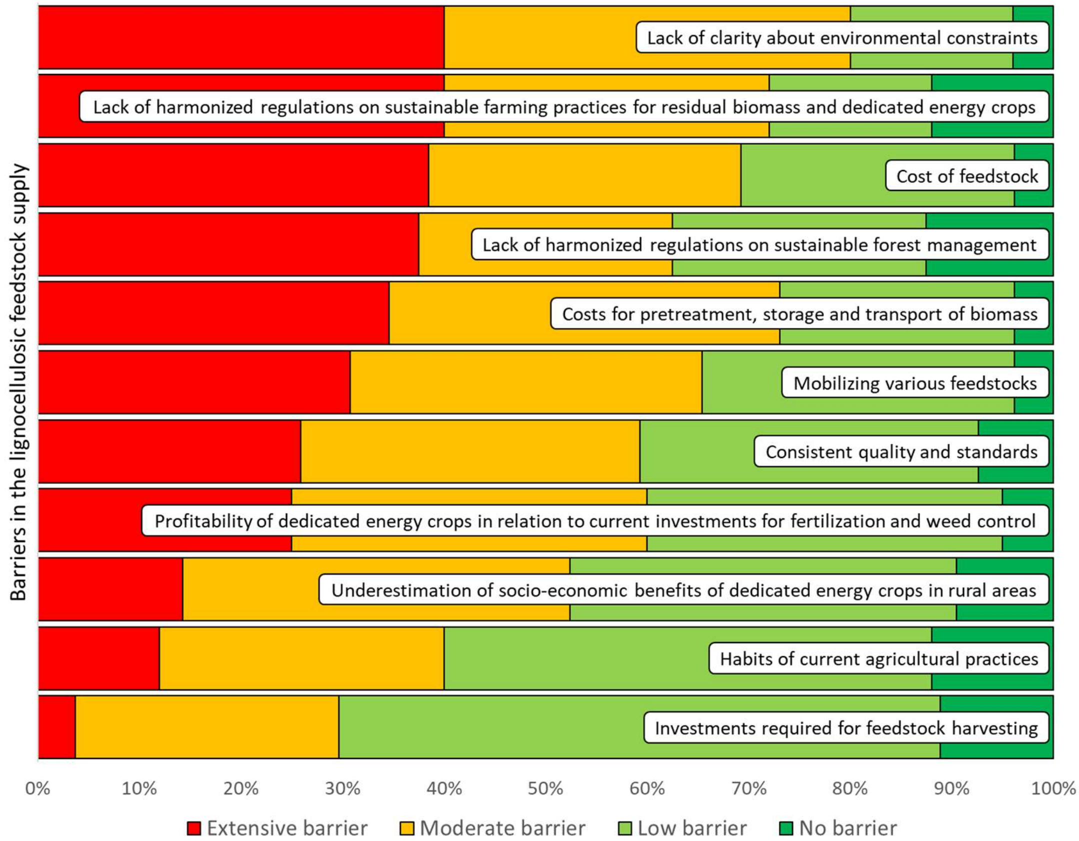

Figure 5 Stakeholder reactions to the barriers relevant to feedstock supply

[9] It included some suggestions for member states to regulate sustainability requirements for solid biomass (mainly residual biomass) used in the electricity and heating sectors.

3.3Conversion technologies

Stakeholders identify the most important barriers related to conversion step as:

- *dedicated policy support*
- *long-term and stable policy support to provide "stability and security for the industry*
- *high cost of renewable H_2*
- *access to project finance*

Overview of the barriers

The main focus of the ADVANCEFUEL project is on conversion technologies that are at the demonstration scale and near to commercial technologies (with TRL levels of 5-9). Therefore, this chapter covers barriers that are relevant to these TRL levels. The flow diagram below (Figure 6), illustrates the main focus.

Barriers related to the conversion step are grouped under three major categories: technical, economic and regulatory barriers, all having strong interlinkages among each other. Table 6 recaps the key barriers related to conversion step.

Table 6 Main barriers related to the advanced liquid fuels conversion step

Barrier category	Barrier description
Technical	Most technologies cannot handle multiple resources, i.e. are dependent on a single resource. Moreover, they are mostly limited to using high quality feedstocks such as wood pellets while there will be an increasing need to use low grade feedstocks such as various waste streams.
	Challenges related to the design of biorefineries with multiple products.
	Limited overall conversion efficiency (insufficient exploitation of the potential of all fractions of biomass).
	High energy intensive processes and/or high chemical consumption.
	In some cases, high consumption of water, phosphate and nitrates.
	Low contaminant tolerance of technologies (e.g. Syngas fermentation) can be disrupted by system contamination from other bacteria, affecting yields and product selectivity.
	Challenges related to integrating conversion technologies into existing (petrochemical) processes (i.e. Very high costs of renewable H_2).
	Demonstration of technical reliability of processes, closing the mass balance and ensuring a high utilisation factor (long operation hours is lacking for some of the conversion routes).

Barrier category	Barrier description
Economic	High capital investment requirement of the commercial production facilities.
	Risks experienced during the emergence of RESfuels restrict access to project finance.
	Limited financial support for research, development, demonstration and early deployment activities.
Regulatory	RESfuels require dedicated policy support (in the form of dedicated targets and incentives).
	Need for long-term and stable policy support to provide stability and security for the industry (including pricing and regulation of (competing) fossil fuels).

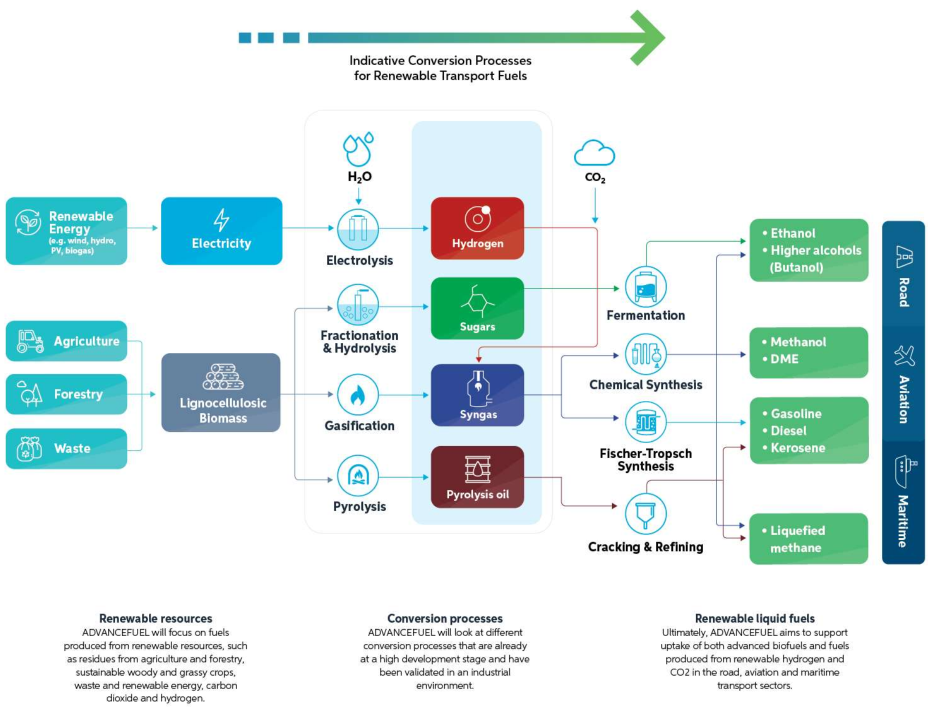

Figure 6 Flow diagram of RESfuels

Barriers common to all technologies

Key challenges relating to RESfuels are summarized below (IRENA 2016):

- A major barrier to large scale lignocellulosic biofuel production is the high capital investment requirement of the commercial production facilities. Capital costs for building lignocellulosic biorefineries vary by the choice of feedstock, the conversion technology, and the size of biorefinery.
- Owing to very high capital costs, there are considerable financial barriers to RESfuels development and deployment. High capital investment requirements combined with risks experienced during the emergence RESfuels restrict access to project finance.
- Related to the above points, limited financial support for research, development, demonstration and early deployment activities pose a barrier as these are needed to reduce some of the risks experienced during the emergence of advanced fuels.
- Additionally, continued subsidy support to fossil fuels (including tax breaks to reduce the price of diesel) (Gençsü et al. 2017) and exclusion of external costs result in low fossil fuel prices. This discourages investments in the biofuel industry.
- The feedstock supply chain is often not constant and offers multiple resources of biomass of various quality. Existing biofuel plants mainly run on (clean) wood chips and wood pellets derived from conventional feedstocks. The differences between the characteristics of wood, straw, stover and vegetative grasses can create particular challenges for bio-conversion in multi-feedstock plants (Berlin et al. 2006). The fact that most technologies cannot handle multiple resources —particularly the low grade ones—is a severe disadvantage and further efforts are needed to develop more flexible technologies. Low grade feedstocks will become more important when demand for biomass feedstocks increases, next to the demand from other sectors.
- The technologies that exploit mainly the cellulose part of lignocellulosic biomass with very basic lignin utilization (e.g., as a fuel itself) result in low overall efficiency. They do not sufficiently exploit the potential of all fractions of biomass that would help them cross a respective profitability threshold and make them more attractive as a whole.
- Challenges related to the design of biorefineries of multiple products (i.e., not only producing a dedicated product-fuel). This is both a technical and economical challenge, since such biorefineries need to be somewhat flexible with respect to their production mix to address challenges from the economic environment (i.e., logistics, prices of fuels and co-products).
- Dedicated targets and incentives to advanced fuels will be essential for innovative technologies with high risks and high capital expenditures.
- In addition to that, only long-term and stable policy support will be able to create sufficient investor confidence in investing in these technologies. Past experiences have shown that many European projects have been delayed as a result of policy uncertainty.

Advanced lignocellulosic biofuel conversion pathways are at different stages of technological maturity. Table 7 presents the technical status and the TRL levels of the relevant conversion routes. Different conversion routes are grouped under biochemical and thermochemical processing and the related technical barriers are presented in Annex I.

Table 7 The status and technical readiness for various types of fuels (Maniatis et al. 2017)

Type	Fuel	TRL level (expected year of development
First-of-a-kind, ready for commercialisation	Cellulosic ethanol, Methanol, DME, Synthetic Biomethane	TRL 8-9 TRL 6-7 TRL 6-7
Innovation ready for first-of-a-kind fuels	Other Lignocellulosic Synthetic fuels	TRL 6-8
Advanced innovation stage	Pyrolysis oils	TRL 5-6

- There is much less focus on less mature technologies (sugar to hydrocarbons, hydrothermal upgrading, alcohol to hydrocarbons aerobic fermentation). Therefore they are not included in the table.

Stakeholder consultation

Figure 7 illustrates the stakeholders' reactions to the barriers that are related to the conversion step. More than 70% of the reactions indicate a lack of **"dedicated policy support"** as the most prominent barrier. They highlight that this is a policy driven market and in the absence of dedicated policy support there will be no RESfuels produced. This is followed by another regulatory challenge. The need for long-term stable policy support to provide **"stability and security for the industry"** (including pricing and regulation of (competing) fossil fuels) is mentioned as an extensive barrier. Investors expect policy support to be stable over a timeframe that is long enough to realize a return on investment.

The high **"cost of renewable H_2"** is listed as a high priority challenge by the stakeholders. This issue is particularly relevant for technologies that use H_2 in their processes, such as production of renewable fuels from non-biological origin (power-to-liquid option) or hydro de-oxygenation of pyrolysis oil to co-feed to an existing refinery.

"Access to project finance" is also highlighted by more than 60% of the stakeholders that filled in the questionnaire. In general, the industry is considered to be a high risk investment, given past failures, high capital costs and reliance on policy support, whereas since 2008 lenders have been more risk-averse, and preferring shorter-term investments (E4Tech, 2017).

Some of the technical challenges included in the literature such as the flexibility of the processes to produce multiple products, technology integration into the existing infrastructure and finally the consumption of chemicals, water, phosphate and nitrate have been indicated as the least challenging barriers.

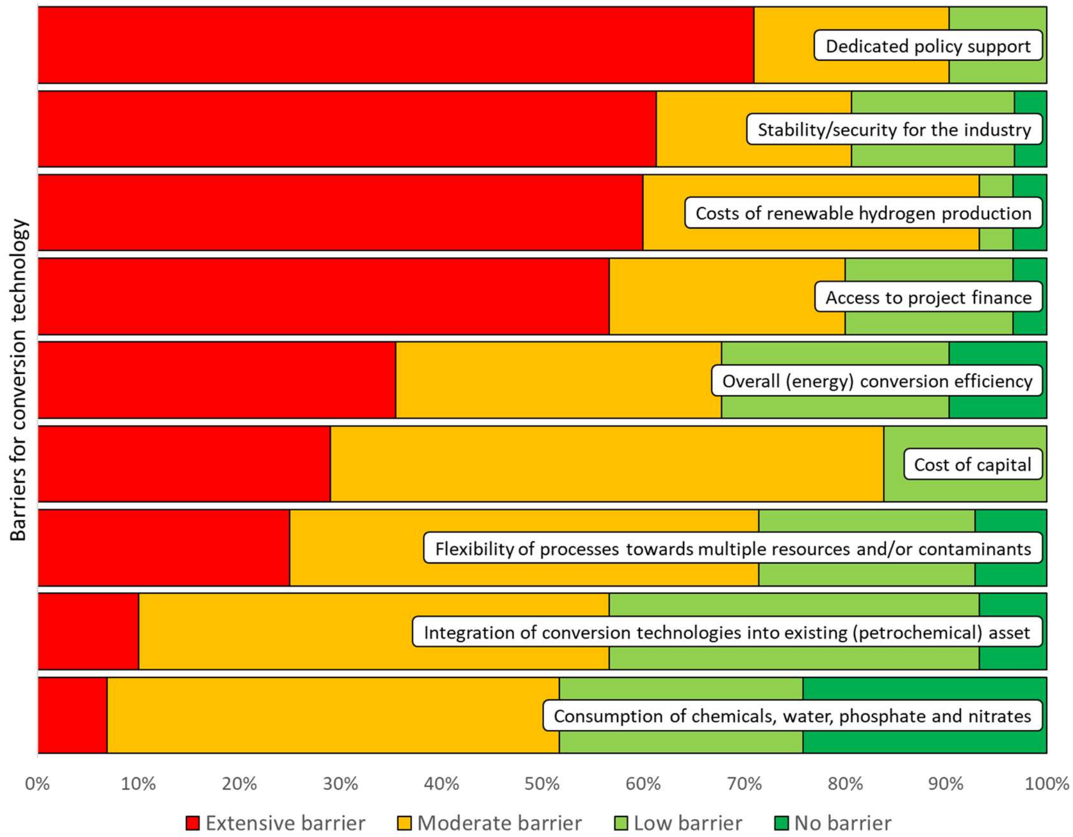

Figure 7 Stakeholders reaction to the identified barriers related to the conversion step

3.4 Distribution and end-use within the transport sector

The top priority barrier listed by the stakeholders regarding the distribution and end-use within the transport sector are:

- *structural financing mechanisms to bridge the price gap between renewable and fossil-based fuels*
- *high production cost of RESfuels in comparison to fossil fuel costs*
- *fossil fuels still receiving subsidy*
- *manufacturers (un)willingness to change*

Overview of the barriers

In contrast to some conventional biofuels, many of the advanced liquid biofuels could literally be added into the existing fuel infrastructure without any changes. They are commonly referred to as drop-in biofuels and can completely replace conventional petroleum fuels, whether gasoline, diesel, or jet fuel. Drop-in biofuels are liquid hydrocarbons that are functionally equivalent and as oxygen-free as petroleum derived transportation blend stocks (fuels).

Among the value chains the ADVANCEFUEL project covers, biofuels produced through FT catalysis and pyrolysis oil upgrading processes result in drop-in biofuels. Ethanol and high alcohols, produced through cellulosic hydrolysis and fermentation are identical to biofuels from conventional sugar and starch crops. Hence, existing barriers related to the conventional biofuels are also valid for these advanced biofuels. Methanol and DME do not belong to the category of drop-in fuels.

In the following paragraphs barriers are presented respectively for road transport, the maritime sector and the aviation sector.

Road transport

Barriers related to road transport are summarised in Table 8 and further explained in the following paragraphs.

Table 8 Categorisation of end-use (road transport) related barriers (Godfroij et al. 2008; de Wilde 2017)

Barrier category		Barrier description
Technical	Vehicle-related	New motor required for non-drop-in fuels.
	Infrastructure-related	Insufficient availability of refuelling infrastructure.
		Slow infrastructure development.
Economic		High costs to construct refuelling infrastructures, or convert existing infrastructure.
		High RESfuel price at the pump, compared to fossil fuels.
		Not enough business opportunities for manufacturers for new technologies.
Social		Lack of customer awareness and market acceptance.
Environmental		Lack of harmonized sustainability criteria for RESfuels for the entire EU.
Regulatory		Lack of harmonisation throughout the EU concerning fuel taxes, biofuel tax reductions and obligation systems.
		Lack of harmonisation throughout the EU concerning applied RESFuel blends and fuel standards.

- New engine technology is required for non-drop-in fuels, like methanol, ethanol, higher alcohols and DME.(de Wilde 2017).
- Not enough business opportunities for manufacturers for new technologies (valid for non-drop-in fuels). While some manufacturers provide vehicles that are able to run on biofuels (e.g. flexifuel[10] vehicles) their competitors are lagging behind. This might indicate that it is not only about technological development but also about creating business opportunities. The fact that in Brazil ethanol cars have been on the road for several decades seems to confirm this (Godfroij et al. 2008; de Wilde 2017). In warm climates ethanol can be used

[10] “Flexifuel” means a vehicle that runs with gasoline or E85 or gasoline-ethanol blend up to 85 %.

more easily than in Europe, as they suffer from less cold-start problems. Technology can be developed in Europe as well when there are enough business opportunities.

- Currently car manufacturers pay a lot of attention to developing hybrid or full electric motors. Several car manufacturers informed that they would reduce their efforts in development of combustion engines. Therefore it is not in line with current trends that manufacturers will make additional investments for new types of motors for non-drop in fuels.
- Insufficient availability and slow development of refuelling infrastructure— end-users that would like to start using biofuels and which have to rely on publicly available fuelling infrastructure only have limited possibilities (Godfroij et al. 2008).
- High costs of constructing refuelling infrastructure, or convert existing infrastructure (Godfroij et al. 2008).
- High RESfuel price at the pump when compared to fossil fuels.
- Lack of customer awareness and market acceptance (Godfroij et al. 2008).
- Lack of harmonized sustainability criteria for RESfuels for the EU—currently, many standards and certification schemes are in use in the EU for voluntary or mandatory demonstration of sustainable production of lignocellulosic material (from various sources) in the EU and from third country imports, and for energy use in general (i.e. heat, electricity or transport fuel). However, the suitability of these standards and schemes is not yet assessed for RESfuels.
- Lack of harmonisation throughout the EU concerning fuel taxes, biofuel tax reductions and obligation systems (Godfroij et al. 2008).
- Lack of harmonisation throughout the EU concerning applied biofuel blends and lack of fuel standards (Godfroij et al. 2008).

Maritime Sector

Barriers related to the maritime sector are summarised in Table 9 and elaborated on in the following paragraphs.

Table 9 Categorisation of end-use (maritime) related barriers (Florentinus et al. 2012; de Wilde 2017)

Barrier category	Barrier description
Technical	Limited expertise within the shipping sector with the handling of some biofuels, including their long-term stability.
	Lack of long-term fuel test data to guarantee the safety and continued reliability of the selected fuel.
Economic	Higher production cost of RESfuels versus prices of marine fuels.
Environmental	Lack of information regarding environmental aspects of RESfuels in the operational situation.
Regulatory	The worldwide level playing field character of legislation for shipping could be a hurdle for the introduction of RESfuels in Europe via prolonging the RED actively towards the shipping sector.
	Lack of a separate fuel standard for using RESfuels in the shipping sector.

The barriers related to RESFuel use in the maritime sector are as follows:

- There is limited expertise within the shipping sector in regard to the handling of some biofuels, including their long-term stability (ETIP 2018). The known R&D projects that investigate the possibilities of using biofuels in ship engines are all private company initiatives, and are applied in operational ships. Public information is limited in availability. So there are still some uncertainties around a full scale introduction of biofuels concerning technical aspects. Only small-scale test results by current market players can possibly give a first orientation regarding the use of biofuels in ships.
- Lack of long-term fuel test data to guarantee the safety and continued reliability of the selected fuel (ETIP 2018)—the Health, Safety, Security and Environmental aspects in the operational situation should especially be investigated further for introduction of biofuels on a substantial scale (e.g. a fixed percentage for every ship to use biofuels) (Florentinus et al. 2012).
- Higher price differential of advanced fuels compared to prices of fossil marine fuels, which are generally cheaper than road transport fossil fuels.
- The worldwide level playing field character of legislation for shipping could be a hurdle for the introduction of RESfuels in Europe including the shipping sector in the scope of the RED. Legislation for shipping is limited to a low level of detail, and not so much EU dominated and highly detailed as for road transport which operates more local/ national. For shipping the International Maritime Organization (IMO) is of major importance and acts on a global scale where a worldwide harmonisation of an agreement on rules and requirements is necessary. This could be a hurdle for the introduction of biofuels in the shipping sector (as long as it was only supported and regulated in a European directive. (Florentinus et al. 2012).
- Lack of a separate fuel standard for using biofuels in the shipping sector. Experiences in road transport and aviation show that such a dedicated fuel standard accelerates market acceptance and introduction of the fuel (Florentinus et al. 2012).

Aviation Sector

Barriers related to the aviation sector are summarised in Table 10 and detailed in the following paragraphs.

Table 10 Categorisation of end-use (aviation) related barriers (E4Tech 2014; de Jong et al. 2017)

Barrier category	Barrier description
Technical	Stringent fuel qualification and certification, due to safety reasons.
Economic	The aviation transport sector is characterized by its capital intensity and long investment cycles (>25 years), which result in slow technological developments (e.g. On design, fuels, engines, etc.).
	Higher cost of renewable jet fuels compared to conventional fossil fuel.
	Competitiveness of the aviation industry and possible market distortion effect of high cost RESfuels.
	Competing demand for the same RESfuel (i.e. From road transport).
	Renewable jet fuel deployment requires substantial research, development and demonstration efforts.
	Stringent fuel qualification and certification demand investment from both airframe and engine manufacturers.
Environmental	Lack of robust sustainability standards to monitor the production of RJF with respect to sustainability and socio-economic indicators.
Regulatory	Lack of a structural financing mechanism to bridge the price gap between renewable and fossil-based jet fuels.
	No target set to use RESfuels in aviation, thus lack of blending obligations.
	Lack of harmonized rules internationally for the use of RESfuels in aviation and lack of aviation fuel standards

The barriers related to RESfuel use in the aviation sector are as follows:

- A high level of safety requirements in the aviation industry resulting in stringent fuel composition and quality and respective certification can be a barrier. This demands investment from both airframe[11] and engine manufacturers. In addition to the accreditation process, the aviation fuels supply chain is subject to a high level of sampling and testing to ensure high levels of safety. Thus, new processes will need to pay particular attention to consistent fuel quality as variability may risk fuels being rejected (E4Tech 2014).
- Higher costs of renewable jet fuels compared to conventional fossil fuel. Fuel costs account for 30%-40% of the operating costs for the aviation industry, and are key to the competitiveness of individual players and the aviation industry (E4Tech 2014). High-cost RESfuels could possibly have a market distortion effect within the sector.

[11] The body of an aircraft as distinct from its engine.

- Lack of a structural financing mechanism to bridge the price gap between renewable and fossil-based jet fuels is considered as an important barrier to foster renewable jet fuel deployment (de Jong et al. 2017).
- In Europe policy mechanisms direct the use of biofuels to the road transport sector through mandates and incentive mechanisms. In absence of any mandates or incentive mechanisms[12] provided for renewable aviation fuels, the aviation sector will lose the competition for the same biofuel that can also be used in road transport. As a result of this unequal policy treatment, fuel substitution in aviation appears to be given lower priority, despite recognition of the long term need for emissions reductions and sustainable fuels in aviation. Instead there are voluntarily mechanisms with no clear and strict implementation rules (i.e. ICAO put forward its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)).
- Renewable jet fuel deployment requires substantial research, development and demonstration efforts (de Jong et al. 2017). The main barriers to development relate to project finance and investment risk (E4Tech 2014).
- Lack of robust sustainability standards to monitor the production of RJF with respect to sustainability and socio-economic indicators. Robust sustainability standards are key to guaranteeing sustainable production and global use of renewable jet fuel. Sustainability standards and schemes, both voluntary and regulatory, are effective instruments for monitoring the production of RJF with respect to sustainability and socio-economic indicators such as land use, biodiversity, resource efficiency, life-cycle greenhouse gas emissions, food competition and labour conditions. Given the international character of the aviation sector, certification procedures should be internationally consistent yet flexible to capture region-specific contexts (de Jong et al. 2017).
- Lack of harmonized, international rules for the use of RESfuels in aviation and lack of aviation fuel standards.

Stakeholder consultation

The stakeholders were requested to evaluate a total of 11 topics and provide their views in regard to the extent that these topics represent barriers towards market uptake. 29 out of 31 participants provided their ranking, whereas 2 stakeholders reacted with 'no idea'. Two topics are listed as extensive (67-69%) to moderate (30-31%) barriers by nearly all stakeholders: **"structural financing mechanism to bridge the price gap between renewable and fossil-based fuels"** and **"high production cost of RESfuel in comparison to fossil fuel costs". "Fossil fuels still receiving subsidies"** is also evaluated as an extensive barrier by 50% of the stakeholders. These three challenges boil down to high costs of RESfuels generation and low fossil fuel prices making RESfuels difficult to compete with. This is particularly relevant for the aviation and maritime sectors. The price gap between RESfuel production costs and the end user willingness to pay for the fuel is higher for fossil jet fuel than for renewable jet fuel. Currently, airlines are generally unwilling to pay more for aviation biofuels than for fossil jet fuels, as a result of unwillingness to pass on higher fuel costs to passengers. When it comes to maritime sectors, even though the production costs of marine RESfuels are likely to be lower or comparable to RESfuels used in road transport (due to the lower quality of fuels used in the marine sector less upgrading/refining is typically needed) marine fossil fuels are significantly

[12] REDII includes a 1.2 multiplier for biofuels used in aviation, however, this may not be sufficient enough to shift lignocellulosic-based biofuels from the road to aviation sector.

cheaper than fossil diesel. Next to that, the shipping industry is also currently generally unwilling to pay more for RESfuels (E4Tech, 2017).

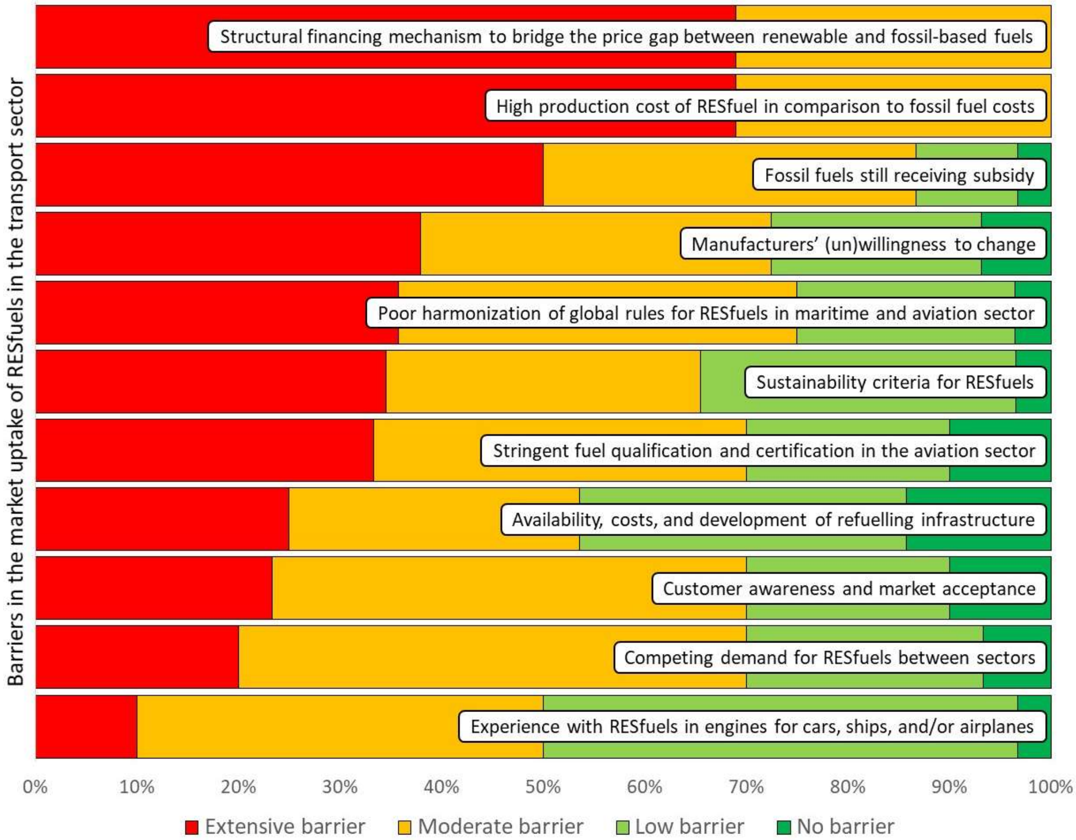

Figure 8 Stakeholders reactions to barriers at the end-use sector.

4. Barriers to RES fuels from non-biological origin

According to the stakeholders the most critical barriers to RESfuels from non-biological origin are:

- *costs of CO_2 capture systems*
- *production capacity of direct air capture*
- *costs of electricity*
- *high energy consumption of the regeneration process of CO2 capture*

Overview of the barriers

Besides RESfuels from lignocellulosic feedstocks the ADVANCEFUEL project also covers renewable liquid transport fuels of non-biological origin. The recast renewable energy directive defines 'renewable liquid and gaseous transport fuels of non-biological origin' as:

"Liquid or gaseous fuels other than biofuels whose energy content comes from renewable energy sources other than biomass, and which are used in transport"

This refers to the route that produces carbon-based liquid fuels from CO_2 and hydrogen where the process is powered by renewable power. The use of CO_2 directly as a carbon source for fuel production opens the possibility to decouple feedstock production from arable land-use. Without the use of natural photosynthesis, however, which stores both carbon and energy, a process is required to capture CO_2 and convert it into fuels (Schmidt et al. 2016). This can be achieved by various approaches; several straightforward routes are depicted below and the technology TRL levels are presented in Table 11.

- CO_2 capture and hydrogenation (with H_2 from electrolysis) to produce methanol
- CO_2 capture and conversion to syngas (with H_2 from electrolysis), followed by FT synthesis
- CO_2 capture and electro-conversion to produce syngas, followed by FT synthesis.

Table 11 Technology status of renewable liquid fuels from non-biological origin (Schmidt et al. 2016)

Type	Fuel/Feedstock	TRL level
First-of-a-kind, ready for commercialisation	CO_2 (point source capture)	TRL 8-9
	CO_2 (air capture)	TRL 5-7
	H_2 (AE)	TRL 7-8
	H_2 (PEM)	TRL 6-7
	Methanol	TRL 7-8
Innovation ready for first-of-a-kind fuels	Diesel (FT)	TRL 5-6
Advanced innovation stage	Syngas (co-electrolysis)	TRL 4-5

All these pathways are energy intensive and should run solely on renewable energy if the final product is to be called a RESfuel. For example, H_2O electrolysis driven by electricity generated from renewable sources (e.g. solar, wind, hydro) produces renewable H_2. This can be used in the first two routes, as shown above, to convert CO_2 into fuel. Such a set-up can be important in order to increase the value of wind and solar, i.e. of variable renewable electricity (vRE).

Table 12 illustrates a short summary of the existing barriers within this field. In the sections below the barriers and challenges are summarized per category. The current status of the technologies involved in the production of fuels via these pathways is presented in Annex II.

Table 12 Barriers related to feedstock supply

Barrier Category	Barrier description
Technical	High energy consumption of the regeneration process of CO_2 capture.
	Stability of the CO_2 sorption materials.
	Concentrated CO_2 sources are limited in terms of the fuel consumption levels.
	Renewable energy/electricity production is often not close to the location of the CO_2 point source complicating logistics and transport of the feedstocks (electricity and/or CO_2).
	Low production capacity of direct air capture (poor mass transfer kinetics and low concentration of CO_2 in air).
	Flexible response of electrolysis is required, if coupled to an intermittent power source or only working when electricity prices are low.
	The synthesis process faces similar barriers to the gasification downstream synthesis processes (see section 3.2)
Economic	Installation of CO_2 capture systems increases the initial investment costs.
	Renewable electricity costs are high making electrolysis expensive.
	Competition for various feedstock and products (CO_2, electricity, H_2, and CH_3OH).
Social	Public awareness of CO_2 as feedstock for fuel production is poor and may suffer from its negative role as a being a GHG.
	The use of CO_2 as a feedstock (CCU) may suffer from concerns related to CCS.
Environmental	The GHG emissions and environmental impacts for CO_2 usage (both from point source and air) are not well analysed and documented.
Regulatory	Certification is required to ensure a market share for CO_2 as feedstock for RESfuels.

4.1 CO_2 capture

Different technologies are employed to capture CO_2 from point sources, each with their own advantages and disadvantages (Siegemund et al. 2017). Typically the CO_2 is washed out from the gas stream via scrubbing with base solution. After capture, the CO_2 is released upon heating, thereby regenerating the scrubbing solution.

The barriers related to this stage are as follows.

- The regeneration process is energy consuming and thus costly.
- Installation of CO_2 capture systems increases the initial investment costs, although the operating costs (no purchase of feedstock) become lower.
- Feedstock competition for various uses exists, such as beverages and chemicals.
- Repeated heating of the material leads to degradation affecting the lifetime of the material.
- Public awareness of CO_2 as feedstock is poor and may suffer from its negative role as being a GHG.
- The use of CO_2 as a feedstock (CCU) may suffer from concerns related to CCS.
- A severe barrier can exist in its dependence on industrial or biogenic CO_2 emitters. Renewable energy/electricity production, as being the other feedstock required for fuel production, is often not close to the location of the CO_2 point source. Logistics and transport of the feedstock (electricity and/or CO_2) can become expensive, thus increasing fuel production costs.
- Concentrated CO_2 sources are limited in terms of fuel consumption levels.

Direct air capture (DAC) technology is developed based on capturing CO_2 either with scrubbing solutions or on solid materials. A clear advantage of DAC, in contrast to point source capture, is its unlimited supply and its ability to be installed where the CO_2 is required, which simplifies the logistics of fuel production. The concentration of CO_2 in air (400 ppm) is, however, much lower than found in most point sources (around 10%). The first six barriers, as stated above, are also valid for DAC.

Other barriers are:

- The low concentration of CO_2 in the atmosphere demands a high air flow through the system; otherwise the production capacity is limited. This requires active air circulation if there is no natural air flow (wind).
- DAC is (at least currently) more expensive than point source capture, although accurate cost numbers are not available due to the early stage of development of DAC technology (Lackner et al. 2012).
- Mass transfer kinetics are poor (gas to solid (or solution) interphase) and hamper production capacity.

4.2Fuel production

Many barriers regarding the synthesis steps are similar to those mentioned in the gasification section downstream processes (FT and Methanol synthesis to produce RESfuels of non-biological origin). Other main barriers for this route are the high costs for CO_2 via capture as already illustrated above. Aside from this, other barriers consist of high production costs of renewable hydrogen via electrolysis, concerns about GHG emissions (van der Giesen & Kramer 2014), and lack of certification:

- If directly coupled to intermittent renewable energy sources, electrolysers need a flexible response. This also creates a demand for novel developments in mature technologies, such as alkaline electrolysis.
- Stability of the materials of high temperature solid oxide electrolysers (SOE) needs to be improved to increase lifetime.
- Costs for energy (renewable electricity) to drive electrolysis are high.
- Renewable electricity is consumed in many other sectors (i.e., electric vehicles, residential electricity consumption, electricity driven processes in various industries).
- Other sectors will compete for the chemicals produced (e.g. H_2 for ammonia production).
- Investment costs are high and even higher if the electrolyser runs at partial load when connected to an intermittent power source instead of to the grid (e.g. only ~20% load factor if directly coupled to solar PV electricity).
- The GHG emissions and environmental impacts for CO_2 usage (both from point source and air) for fuel production are not well analysed and documented (von der Assen et al. 2013).
- Certification is required to ensure a market share for CO_2 as a feedstock for fuels.

Stakeholder consultation

10 topics are listed as the main challenges related to CO_2 and renewable electricity supply for the production of RESfuels from non-biological origin. Among the 31 participants, 25 reacted to this section of the questionnaire, and their views have been illustrated in Figure 9. The three most prominent barriers mentioned by the stakeholders are the "**costs of CO_2 capture systems**", the **"production capacity of direct air capture**", and "**costs of electricity**", which are evaluated by 41-50% of the experts as extensive.

Most topics are considered to be a moderate or extensive barrier by around 50% of the stakeholders, which agree well with the literature information. Only "availability of concentrated CO_2 sources" is mentioned as low or no barrier by the majority of the participants (58%). It is remarkable that the two stakeholders that explicitly mentioned their expertise in this part of the value chain, rate "costs of CO_2 capture systems" and "energy consumption of the regeneration process of CO_2 capture" as low barriers, while respectively 50% and 40% of the other participants asses these topics respectively as extensive barriers. This shows that the results of such a survey should be handled with care as they can strongly depend on the expertise of the participating stakeholders.

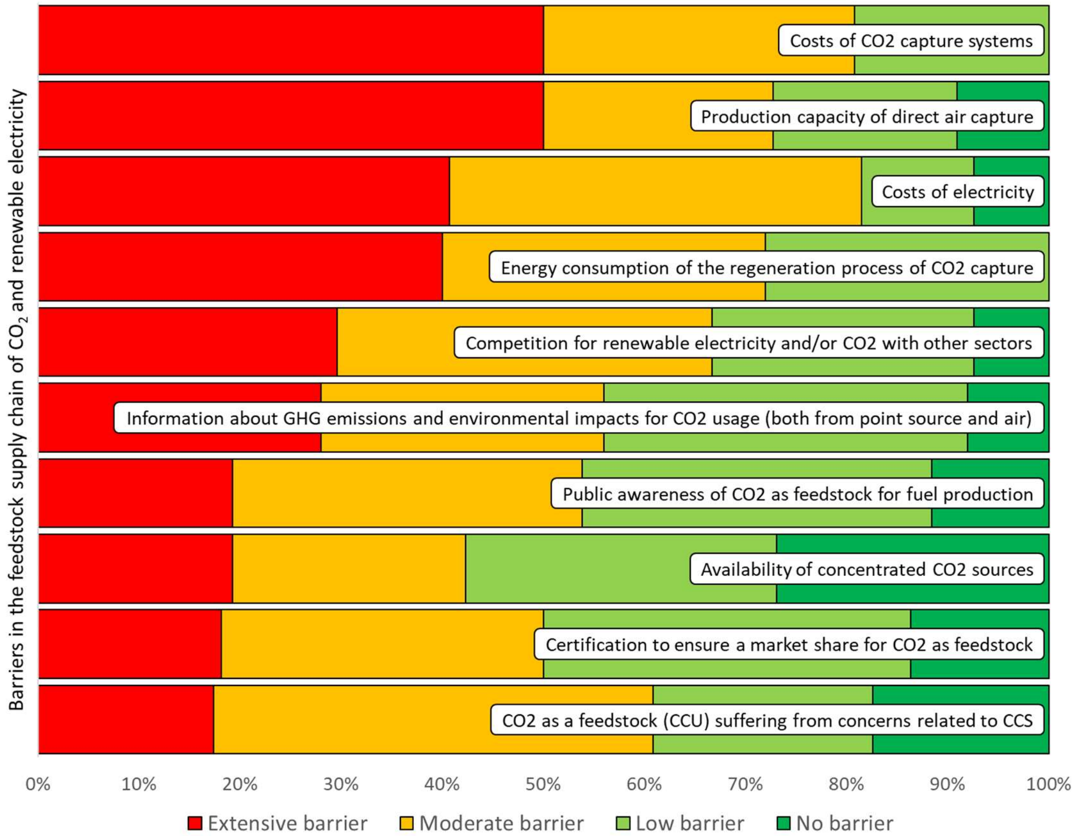

Figure 9 stakeholder reactions to barrier identified for Res fuels from non-biological origin

5. Conclusions and discussions

Conclusions

An extensive literature review has resulted in the identification of a large number of challenges that may hamper the market uptake of RESfuels.

The questionnaire's results show that almost all of the topics reviewed in literature are considered to be moderate to extensive barriers by 50% or more of the stakeholders, except some of the feedstock related challenges such as investments required for feedstock harvesting and habits of current agriculture practices, and the availability of the concentrated CO_2 sources.

Among the barriers per section "dedicated policy support" (71%), "structural financing mechanism to bridge the price gap between renewable and fossil-based fuels" (69%), "high production cost of RESfuel in comparison to fossil fuel costs" (67%), "stability/security for the industry" (61%), and "costs of renewable hydrogen production" (60%) are considered to be high barriers by a large number of stakeholders. The availability of concentrated CO_2 and the consumption of chemicals, water, phosphate and nitrates received the highest share of "no barrier" reactions from the stakeholders (>20%). Next to these, habits of current agriculture practices, investments required for feedstock harvesting, integration of conversion technologies into existing petrochemical assets and experience with RESfuels in engines for cars ships and/or airplanes have been marked as “low barriers” by a relatively large number of stakeholders.

In an open answer section, the stakeholders also mentioned several other barriers, which are not part of the listed topics, such as competition with countries outside the EU, diverging fuel quality standards, lack of optimization of a specific value chain, lack of renewable electricity and grid capacity, patent protection, and vehicle tank-to-wheel CO_2 regulation. The open answer section was also used by several of the experts to again emphasize the top 5 barriers as mentioned above. Price is seen as the major obstacle, as competition with fossil fuels seems currently impossible. To achieve market competitivity, a reduction in RESfuel production costs, improved regulations (e.g. common framework for LCA, well-to-wheel-based CO_2 regulation, technology neutrality) and long-term policy support are required according to most of the stakeholders. Next to these, a structural financing mechanism to bridge the price gap between renewable and fossil-based fuels seems strongly desirable.

In the ADVANCEFUEL project, WPs 2-6 will analyse the barriers in more detail and provide innovative solutions to overcome them. There will be a particular attention to the barriers that were highlighted as extensive by the stakeholders. A summary list of the barriers considered to be extensive by the stakeholders is presented below:

Table 13 Summary of top 4 priority barriers based on the stakeholders reactions

Type of barrier	Name of barrier
Lignocellulosic feedstock supply	
Environmental	Lack of clarity about environmental constraints
Regulatory/ environmental	Lack of harmonised regulations on sustainable farming practices for residual biomass and dedicated energy crops
Economic	High cost of feedstock
Regulatory/ environmental	Lack of harmonised regulations on sustainable forest management
Conversion step	
Regulatory	Absence of dedicated policy support
Regulatory	Concerns on stability/security for the industry
Economic	Cost of renewable H_2 production
Economic	Access to project finance
End-use	
Regulatory	Absence of structural mechanism to bridge the price gap between renewable and fossil-based fuels
Economic	High production cost of RESfuels
Regulatory/economic	Fossil fuels still receiving subsidy
Economic	Manufacturers unwillingness to change
RES fuels of non-biological origin	
Economic	Cost of CO_2 capture systems
Technical	Production capacity of direct air capture
Economic	Cost of electricity
Technical	Energy consumption of the regeneration process of CO2 capture

Discussions

The barriers are grouped and presented under different stages of the RESfuel value chain. It is, however, necessary to highlight that these barriers are for the most part interlinked with each other. For instance, the high cost of feedstocks listed as a barrier in feedstock supply relates very much to the high production cost of RES fuels listed as a barrier to end-use. Manufacturers' willingness or unwillingness to change relates very much to the profitability of the business case. The RESfuels' high production costs and the absence of financing mechanisms to bridge the gap between fossil fuels and RESfuels result in unfavourable business cases for manufacturers. Therefore, further detailed analyses of the barriers will require a more integrated approach that takes into account the interlinkages among the different barriers.

The prioritization of the barriers depends very much on the type of stakeholders who participated in the consultation. The literature reviewed barriers were simplified and converted into an easy to fill out questionnaire. The aim was to receive as much feedback as possible with decent representation from different sectors that take part in the RESfuel value chain. It has been sent to around 100 stakeholders. We also attended several events (ETIP Bioenergy Plenary, NextButanol Conference, EUSEW event) to meet with the stakeholders and encourage them to take part in the survey. This resulted in reactions from 31 stakeholders, of which around 40% were from research organizations and academia. This is followed by industry related stakeholders (~25%). Agriculture and forestry related stakeholders and the consultants were the next largest stakeholder group that participated in the questionnaire. Unfortunately, the end-use related stakeholders were limited to 6% of the total participation.

Finally, it is necessary to highlight that this questionnaire was still susceptible to the usual shortcomings questionnaires may face. While the questionnaire was kept short and simple to answer (with mostly multiple choices), there was still the risk that different stakeholders may have had different interpretations of the questions, resulting in subjective answers.

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Annexes

Annex I Barriers related to biochemical and thermochemical downstream processes

Biochemical processing

The biochemical processing route consists of extraction/hydrolysis of lignocellulosic biomass, followed by the fermentation process to produce ethanol or butanol. Pre-treatment technologies for the biochemical processing are recognised as the most expensive process steps and the most technically difficult tasks (IRENA 2016).

The main technical barriers for the extraction/hydrolysis process are listed as follows (Chiaramonti et al. 2012; Harmsen et al. 2013; IRENA 2016):

- Insufficient separation of cellulose and lignin in the pre-treatment step reduces the effectiveness of the hydrolysis step and therefore overall conversion efficiency.
- Severe pre-treatment conditions cause degradation products which can inhibit downstream fermentation.
- Pre-treatment and hydrolysis steps are energy-intensive and/or use a high amount of chemicals leading to increasing operational costs and reducing energy efficiency.
- Enzymatic hydrolysis routes suffer from their selectivity for a specific feedstock, limiting the overall flexibility.
- Low feedstock quantities as the solid loading of enzymatic hydrolysis is often limited. This results in low product concentrations and large mass flows to be treated downstream.

The downstream processes consist of fermentation to ethanol, methanol, DME and butanol. The main barriers can be summarized as lower yields due to either limited capacities of C5 and C6 sugar fermentation or production of different co-products and energy intensive recovery process.

Biochemical route downstream processes

Fermentation to Ethanol

Production of cellulosic ethanol is at a relatively advanced stage with several operating industrial scale first-of-a-kind plants using agricultural residues. Technologies based on forestry residues still have to reach the level of industrial-scale demonstration[13]. Technical improvements

[13] Different technologies are under development for the hydrolysis step. These include hydrothermal pre-treatment (chemical free, steam pre-treatment followed by enzymatic hydrolysis) as used by Beta Renewables (Italy), and Clariant (USA) and Inbicon (Denmark), and thermo-chemical pre-treatment (dilute ammonia pre-treatment followed by enzymatic hydrolysis) as used by Abengoa (USA) and Dupont (USA). Several different types of sugars are produced (namely C5 and C6 sugars), which are then fermented into ethanol (most fermentation processes convert C6 sugars although C5 sugars can also be fermented simultaneously by some processes). The fermentation can take place in a separate reactor, or (partially) in the same reactor as the hydrolysis step. The reactor set-up depends amongst others on the enzyme technology available and the value of co-products (Ecofys, 2015).

are needed to improve the economics of the process and the prospects for ethanol production (Humbird et al. 2011; US DOE 2012; Wagner & Kaltschmitt 2013).

- Limited capabilities of C5 and C6 sugar co-fermentation: the yeast performance affects the yield, rate, capex and cost of ethanol from the process. Continuous development is needed to improving yeasts by selecting the best host organism, identifying and modifying individual genes to put in the host and optimising the yeast and the process conditions in the plant.
- Energy-intensive ethanol recovery caused by low ethanol concentration: distillation is typically used for separating and purifying but is an energy intensive process. Advanced separation techniques[14] are needed. Advanced separation technologies are being developed at the laboratory scale. These techniques still need to be scaled up and demonstrated before they represent a commercially available solution.

Fermentation to methanol and DME production

Following the fermentation process, the biogas has to be cleaned to obtain a gas with a high methane content, after which methanol (MeOH) is then produced from the methane.

Methanol may be converted to dimethyl ether (DME) for use as a diesel replacement or to gasoline and diesel range hydrocarbons. Barriers to its use include concerns about human toxicity and corrosive effects on conventional engines.

Fermentation to butanol

Fermentation to butanol is indicated to be similar to ethanol but with additional technical barriers mainly related to product selectivity. Details of the additional barriers are listed by IRENA (IRENA 2016):

- Butanol fermentation has been optimised for high sugar content feedstocks, which are more expensive. Conversion of low sugar content substrates (and therefore lower-cost feedstocks) to butanol needs further R&D.
- The inhibition of fermentation organisms by the fermentation products means that the process must take place with high dilution and low product concentration in the fermentation broth. This consumes a large amount of energy in the product separation stage.
- Acetone and ethanol are produced as co-products limiting the yield of butanol and increasing the complexity of product separation (e.g. liquid-liquid extraction), which can be very energy-intensive. The co-fermentation of both C5 and C6 sugars is a bottleneck in the process. Solving this issue can maximize the alcohol yield. Especially for butanol production, the selectivity of the yeasts is not very high and suffers from co-product formation.

[14] Such as membrane separation/osmosis and induced phase separation.

Thermochemical processing

The focus is on two conversion routes; gasification and pyrolysis.

Gasification is a thermochemical process occurring with a shortage of oxygen at temperatures around 750-1000°C. The biomass in this process is degraded into specific small molecules, mainly carbon monoxide and hydrogen. The produced syngas can be used in various fuel producing downstream processes resulting in biofuels such as methanol/DME, bio-methane and Fischer-Tropsch (FT) diesel. Typically, the economic capacity of a gasification plant is significantly higher than that of a lignocellulosic ethanol plant, creating pressure on investment capital (Maniatis et al. 2017).

Barriers/obstacles experienced with this technology are listed below.

- The more established gasification systems require high quality, homogeneous feedstocks in order to operate reliably and efficiently[15]. Biomass feedstocks often create processing problems unless they are homogenized in other processes (pyrolysis, torrefaction or fractionation). More flexible gasifiers have to be developed to overcome these problems.
- Another problem is the formation of tar[16], which causes clogging and corrosion. Purification of the raw syngas is required to remove dust, alkali metals, halogens, sulphur, tars and potentially CO_2 before conversion in subsequent processes. In some cases these gas cleaning methods generate significant amounts of contaminated waste water.

The downstream processes suffer from contamination (e.g. sulphur in the syngas feed), resulting in short catalyst life time, low selectivity to yield deserved products and high energy demand. This increases the complexity of the processes and results in higher capital costs.

Although gasification-based routes and the FT processes involve mature technologies, there is very limited experience in integrating biomass gasification with downstream processes for the production of liquid transport fuels. The challenge is to achieve the scale-up of such technologies and ensure their technical reliability and long operation.

Pyrolysis and upgrading

Pyrolysis is a thermal process that occurs with a temperature of around 500°C. There are a few companies implementing the process on a commercial scale to produce crude pyrolysis oil[17]. For application in the transport sector, the crude pyrolysis oil needs further upgrading either by hydrotreatment in a dedicated facility or can be co-fed[18] with petroleum oils in refineries (FCC reactors). Integration of pyrolysis oil into the exiting oil refineries can have great advantages, such as reducing biofuel production capital and operating costs. The hydrotreatment route involves steps to separate water from pyrolysis oil, remove oxygen, nitrogen, sulphur and saturate olefins and certain aromatics. The result is hydrogenated pyrolysis oil (HPO) that can be blended

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15 However, the GoBiGas plant (indirect gasification) runs on wood chips from forest residues (Johnsson 2018).

16 A better utilisation of tar for extraction of chemicals (i.e., again need for advancing technologies from TRL 3 to 5-6) can add value from the system perspective.

17 Ensyn operates a commercial facility in Ontario, Canada since 2014 to produce pyrolysis oil for industrial heat and another commercial facility by Empyro-BTG has produced pyrolysis oil for electricity and industrial heat in the Netherlands since 2015.

18 Co-feeding 5-10% of pyrolysis oil with vacuum gas oil in existing refineries has been attracting attention.

directly with fossil diesel, or a mix of diesel and petrol when resulting from hydrotreatment and distillation in fossil refineries (Peters et al. 2015).

The technical barriers for this conversion route are:

- Pyrolysis produces solid, liquid and gaseous fractions. Only the liquid fraction is converted to liquid transport fuels. Maximising liquid production is therefore necessary to realise the potential yields. The presence of feedstock ash can dramatically reduce liquid yields.
- Pyrolysis oil is typically unstable and has high acidity, viscosity and water content, and a tendency to polymerise. These characteristics make storage and downstream processing problematic.
- High water and oxygen content of the bio-oil inhibits the catalysts in downstream processes. Optimization of the processes is required to improve the liquid product yield and to decrease the water and oxygen content.
- Limited availability of low cost sustainable hydrogen.
- High water content within the feedstock and large amounts of waste water discharge during the process that contains significant amounts of organic material that requires high-cost purification steps.

Thermochemical route downstream processes

Fischer-Tropsch catalysis

The synthesis gas can be chemically converted to a hydrocarbon product using FT catalysis. The FT catalysis produces carbon chains of various lengths, which can subsequently be cracked into chains of the preferred length such as needed for diesel or kerosene (Peters et al. 2015). The process also involves complex gas cleaning steps to remove tars, as well as alkali and halogens from the gas that could poison the catalyst. Commercial production of FT renewable diesel from wood has been tried by several companies and consortia. So far, it has proven difficult to bring the technology to commercial scale. There are a small number of plants in early operation and in the pilot stage.

Technical barriers and needs relating to the commercialisation of FT synthesis for advanced biofuels are listed below (Hannula & Kurkela 2013; IRENA 2016; Tuna & Hulteberg 2014; US DOE 2012).

- The FT catalysts suffer from contaminations, e.g. sulphur, in the syngas feed. This causes very short catalyst lifetime and reduces the selectivity to yield specific product ranges. As a consequence, the upgrading and purification processes become more difficult.
- Selectivity to required diesel, jet or gasoline fractions are typically limited to less than 40%. Significant amounts of unwanted olefins, alcohols, acids, ketones, water and CO_2 are also produced.
- The FT reactor design influences catalyst lifetime and reaction rate. Carbon deposition in fixed bed reactors results in catalyst deactivation. In fluidized bed reactors, catalysts are lost due to entrainment in the gas stream and attrition. The reactor design also affects heat and mass transfer limits.
- The ratio CO/H_2 is very specific for FT synthesis and sometimes additional H_2 is required, which is often prepared by the water gas shift reaction converting CO and H_2O into CO_2 and H_2. This adds to costs and loss of yield because CO_2 is emitted to produce hydrogen.

- FT catalysts produce a range of hydrocarbon products, including waxes. These must be upgraded and fractionated to end production. This is achieved through hydrogenation, isomerisation, reforming, cracking and distillation. This increases the complexity of the process and therefore capital costs.

Syngas fermentation

Syngas can be fermented to produce ethanol, butanol and a range of chemical products. This is a relatively new technology developed by a limited number of developers. Technical barriers and needs relating to the commercialisation of syngas fermentation for advanced biofuels are as follows (Daniell et al. 2012; Griffin & Schultz 2012; IRENA 2016; Wagner & Kaltschmitt 2013):

- Consumption of a significant amount of energy at the product separation stage (typically distillation): the process must take place at a high dilution and the concentration of product in the fermentation broth has to be low to inhibit fermentation organisms through fermentation products.
- Current technology has low gas-to-liquid mass transfer resulting in low volume specific conversion. This creates a need for large system components (e.g. reactor vessels). This raises capital and operational costs in pumping liquids and bubbling gases.
- Syngas fermentation can be disrupted by system contamination from other bacteria, affecting yields and product selectivity. Trace species in the syngas can also cause population loss. The sensitivity of the fermentation organisms to hydrogen cyanide, tars, hydrocarbons, and other bacteria is one of the technical challenges encountered.
- Acetic acid is produced as a by-product, reducing ethanol yields.
- High consumption of water, phosphates and nitrates.

Mixed alcohol synthesis

Mixed alcohol synthesis produces a mixture of methanol, ethanol and higher alcohols. Catalyst systems are indicated to be commercially available, but have not been commercially applied for the conversion of biomass-derived syngas (IRENA 2016). The syngas requirements are very similar to FT-catalysis. The exception is the required hydrogen to carbon monoxide ratio, which needs to be only 1:1.2.

Technical barriers and needs relating to commercialisation of mixed alcohol synthesis for advance biofuels are listed as (Atsonios et al. 2013; IRENA 2016; Wagner & Kaltschmitt 2013):

- Commercially available catalysts typically achieve low syngas conversion per pass, resulting in the need for recycling and large process systems at greater capital and operational cost.
- They also have low selectivity towards desired alcohols and operate at high pressure, resulting in a high energy demand.

Methanol synthesis

Natural gas based methanol hydrolysis is commercially proven technology. Methanol synthesis of syngas from lignocellulosic biomass based gasification is at an early commercial stage. There are a few early commercial plans based on glycerine cracking or wastes.

- Current road transport fleets in many regions are limited in their ability to use methanol. Therefore this methanol may need to be catalytically converted to gasoline.
- The reaction is highly selective; the syngas has to be cleaned of contaminants and conditioned to meet the catalyst specifications. Syngas clean-up requirements are similar to those of FT synthesis.

- For methanol synthesis, 4%-8% CO_2 is typically required to catalyse the reaction. Some of the FT barriers relating to sulphur poisoning and catalyst lifetimes also apply, as does the need to avoid alkali metals (to prevent mixed alcohol synthesis).
- Greater demonstration of contaminant tolerance in large-scale plants using new biomass or waste feedstocks will be required to guarantee future performance.

Annex II Current status of liquid renewable alternative fuels

CO_2 capture

Sources of CO_2 are available in two main grades: relatively high concentrations of CO_2 (from industrial or biogenic point sources), and low concentrations of CO_2 (from atmosphere and oceans). Technology to capture the CO_2 from industrial or biogenic waste streams is available at commercial scale thanks to achievements made in CCS approaches. Globally, more than 31 Mt/year of CO_2 is captured from industrial sources (e.g. at steel mills, power plants, and cement factories) of which most is used in enhanced oil recovery (Irlam 2017). Instead of pumping the isolated CO_2 underground, using it as a feedstock for the production of fuels and chemicals may be advantageous.

Another approach is to capture the CO_2 from the atmosphere, similar to in natural photosynthesis. This can be achieved by direct air capture (DAC) technology and is currently in the developing stage (TRL 5-7) (Lackner et al. 2012). Several companies (e.g. ClimeWorks, Carbon Engineering) have their first pilot systems up and running, capturing ~1000 ton CO_2/year (Gale 2015). The next step is to deploy large scale DAC installations.

Electrolysis

The most evident route to produce renewable H_2 is through electrolysis driven by renewable electricity. Alkaline electrolysis (AE) has been a commercial technology for many decades and already has a global cumulative installed capacity of more than 20 GW (Detz et al. 2018). Other electrolysis technologies, such as polymer electrolyte exchange membrane electrolysis (PEM) and high temperature solid oxide electrolysis (SOE), are also available at different stages of development. PEM is currently providing system scales of typically 1 MW of installed capacity, while within the H2Future project a 6 MW PEM electrolyzer has been developed (Bertuccioli et al. 2014; Lymperopoulos 2017). The first demonstration units of SOE have a capacity of ~150kW (e.g. Sunfire GmbH).

SOE systems are also developed that can produce syngas directly from CO_2 and H_2O, in so-called CO_2/H_2O co-electrolysis units. Although this approach is in an early development stage (15 kW pilot scale, Idaho National Laboratory), it is a promising route for forming syngas for FT synthesis of liquid hydrocarbons.

Renewable electricity

The energy intensity of the processes that convert CO_2 into fuel require low-cost renewable energy supply. For electrolysis, this energy is mainly provided in the form of electricity. Many technologies are available to supply this energy, such as solar photovoltaics, wind power, hydropower, geothermal power, and tidal power. Cost reductions for these approaches are important for the deployment of electroconversion methods (e.g. electrolysis) to produce fuels.

Methanol production

The first commercial plant to produce "green" methanol was deployed by Carbon Recycling International (CRI) in Iceland (Stefansson 2017). The electricity from a geothermal powerplant is used to produce hydrogen by alkaline electrolysis. In addition, CO_2 emissions from the power-plant are captured and used together with H_2 in a synthesis reactor producing methanol (see also section 3.2.2.4). Also in other (pilot) projects CO_2 is used as feedstock for methanol production (MefCO2, Stepwise, GreenSynFuel, Qafac, FReSMe).

Diesel production

Audi, Sunfire GmbH, and ClimeWorks have built the Sunfire plant, which operates according to the power-to-liquid principle, to produce synthetic diesel. As feedstocks, CO_2, H_2O and electricity are required. The CO_2 is extracted directly from the ambient air using direct air capture technology from Climeworks. Solid oxide electrolyzers powered with green electricity split H_2O to produce H_2 (Sunfire 2016), which is then reacted with the CO_2 to generate syngas by means of the reverse water gas shift reaction. The syngas is fed into an FT reactor producing, after refining, synthetic diesel. In this first-of-a-kind pilot, plant diesel is produced at 130 L/day scale.