European Commission

LOW CARBON ENERGY OBSERVATORY

SUSTAINABLE ADVANCED BIOFUELS

Technology development report

Joint Research Centre

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Contents

Foreword about the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use of private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

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1 Introduction

This Technology Development Report for 'Sustainable Advanced Biofuels' is an update to the version produced in 2018. Since then, the Renewable Energy Directive (RED) the so-called 'recast' of 2009/28/EC has been published (Directive 2018/2001 or REDII). It contains a 14% target for renewable energy in transport by 2030, an increase from the previous 10% level, with a new advanced biofuels sub-target of 3.5%. In addition, it has been confirmed advanced biofuels will count double towards the target, however biofuels in Annex IX, Part B will be counted only up to 1.7%. The production of conventional biofuels will be frozen at national level at 2020 values +1% but must not go beyond the 7% level (Member States with a share of conventional biofuels less than 2% can still reach the 2% level).

In December 2019, the European Commission presented the 'European Green Deal' that represents a new growth strategy aiming to transform the EU into a fair and prosperous society, with no net emissions of greenhouse gases in 2050 (COM(2019) 640). In order to move to a clean, circular economy and stop climate change, the EU Green Deal provides a roadmap with actions to boost the efficient use of resources. It covers all sectors of the economy, including transport. Transport accounts for a quarter of the EU's greenhouse gas emissions and it is still growing. In order to achieve climate neutrality, a 90% reduction in transport emissions is needed by 2050. Accelerating the shift to sustainable and smart mobility is one of the elements of the European Green Deal and the ramp-up of the production and deployment of sustainable alternative transport fuels, including advanced biofuels is one of the objectives.

The definition of 'advanced' biofuels is not univocal since the term advanced can refer to various attributes of the value chain. In this report, we consider advanced, those technologies capable of converting lignocellulosic feedstocks (i.e. agricultural and forestry residues), non-food and non-feed biomass (i.e. grasses, miscanthus, algae) and biogenic waste and residues (e.g. biogenic fraction of municipal solid waste and animal manure) into transportation fuels and having high greenhouse gas emissions savings, and zero or low indirect land use change (ILUC) impact.

Currently, advanced biofuels production for the transport sector remains limited on a commercial scale mainly due to technological challenges, although in the last decade, there has been considerable progress in technology development as discussed within this and previous reports. The move towards advanced biofuels in legislation has been happening for some time; the previously mentioned RED was updated in 2015 by Directive 2015/1513, which limited the amount of first generation biofuels which can be used in the EU. In addition, biofuels made from straw and non-food cellulosic material began to be counted double towards RED 10% renewable energy target in all forms of transport.

Advanced biofuels technologies have been classified into three main categories, namely following the biochemical, thermochemical or oleochemical route; each technology includes a number of sub-technologies that are analysed in this report.

The **main changes compared to the 2018 version of the report** include: updates on the technology state of the art section; latest available data on patents; new recently started H2020 projects; focus on closed projects for their impact assessment and update on the status of some on-going projects in each sub-technology; a new scenario (called SET plan scenario) included in the modelling results providing a foresight perspective. Trends, barriers and conclusions presented in the 2018 report remain still valid at the time of writing this report.

This report does not include technologies that don't use biomass as main feedstock such as power to fuel (electro-fuel) processes that are part of another technology development report, namely 'Advanced alternative fuels'.

Main characteristics of the technologies included in this report

Lignocellulosic biomass can be **bio-chemically** converted to bioenergy carriers using living microorganisms (fermentation). The basic steps of the conversion process are: a) pretreatment of the biomass, usually thermal or thermochemical, to disrupt the cellular structure of biomass and facilitate access to enzymes; b) enzymatic hydrolysis, to break the large carbohydrates present in biomass (cellulose and hemi-cellulose) down into monomeric C5-C6 sugars; and c) fermentation of the sugars to alcohol using yeasts, other species of fungi or bacteria. The typical alcohols produced are ethanol, n- or i-butanol. These alcohols can be used directly as fuels, or in chemically modified form. Substrates for fermentation can come from a range of biomass sources such as: dedicated energy crops (both grassy and woody) from agriculture and forestry; by-products and waste from agriculture, forestry, wood products industry, pulp and paper industry, food and feed processing industry; organic household waste; or grass, garden and park cuttings. Plants with higher density, lower water content, high growth rate with little care and easy storability and fermentability are preferable but not always available in sufficient amounts. Not all substrates are suitable for all technologies. The development of energy and cost-effective pretreatment methods, more efficient enzyme mixes for the hydrolysis step, and the effective conversion of pentose sugars remain considerable challenges. Currently, the process of ethanol production from lignocellulosic materials is not yet fully commercial, although there are demo plants which are commercial scale.

Lignocellulosic materials, organic fraction of Municipal Solid Wastes (MSW) and other complex waste streams (i.e. wastewater treatment sludge) can also be used for biogas production via anaerobic digestion (AD). The use of waste streams either as primary or as a co-feedstock requires pretreatments, mainly by means of either a) mechanical and thermal process (e.g. steam explosion) or b) biological pre-processing, with enzymes addition. The produced biogas, a mixture of CO_2 and CH_4, can then be upgraded to biomethane to be injected in existing natural gas infrastructure or to be distributed as a fuel for transport. The residues of anaerobic digestion (both the liquid as well as the solid phase) are typically used as a fertilizer, with also positive effects in improving soil structure. The production of biogas, even from various feedstocks, is today a mature technology, whereas the use of more complex feedstocks, biomethane upgrading and digestate management and valorization can still be improved.

Thermochemical conversion technology options can convert lignocellulosic materials, such as forest and woody resources, and lignin-rich, non-fermentable residues, to synthetic fuels and chemicals. Thermochemical conversion can follow three main pathways: a) partial oxidation of biomass to syngas (mixture of H_2 and CO) at high temperature, i.e. typically above 800 °C and pressure. The syngas is then converted into fuels or chemicals via methanation or Fischer-Tropsch (FT) synthesis; b) fast pyrolysis in the absence of oxygen up to temperatures in the range of 450-600 °C to produce a liquid mixture of bio-oils (pyrolysis) that can be further processed into liquid fuels to be used as a replacement for transport fuels; c) hydrothermal liquefaction at moderate temperatures (around 250-550 °C) in the presence of a catalyst for 20-60 min to liquefy and deoxygenate biomass.

Biomass gasification can be accomplished using different reactor types suited to different scales of operation; each of them is a compromise between gas quality, conversion efficiency, suitability for feedstock handling, the complexity and scalability of design or operation, and investment costs. Syngas quality is determined by the combination of feedstock properties, reactor type and the oxidant used for the process. Oxidants can be air (the cheapest option and suitable for small scale systems) or can include other gases such as steam or oxygen, where available and justified by the improved syngas quality. Air gasification does not produce a suitable syngas for the production of synthetic fuels and chemicals. Depending on the proposed end-use of the syngas, the clean-up requirements prior to use or secondary processing will be different. Traditional applications for gasification have included producing ammonia for fertiliser production, fuel gas for domestic and industrial use (e.g. firing ceramic kilns) and syngas for subsequent processing as liquid fuels.

During the last decade, the biofuel sector has shown a considerable capacity of technological improvement, by shifting from first generation bioethanol and biodiesel to **drop-in biofuels**. A drop-in biofuel is an oxygen-free molecule, functionally equivalent to petroleum transportation fuels. There are many solutions for producing drop-in biofuels, mainly based on oleochemical, biological or thermochemical processes.

Most biological processes use sugars as feedstock for fermentation to various alcohols (e.g. ethanol, iso-butanol, etc.), that can successively be upgraded to drop-in fuels. These pathways are currently using existing first generation ethanol plants for producing the feedstock for the biojet sector (i.e. GEVO Inc. in US).

Despite the theoretical potential of biological and thermochemical routes, the current biofuel market is dominated by oleochemical production; mostly because this technology is well developed, and has relatively low technological risks and low capital expenditure compared to other production routes. In traditional oil refineries, hydrogen has been always used to upgrade low grade crude oil, by removing sulphur and other impurities; these steps are generally referred with the term hydrotreating. Moreover, hydrogen is also used to crack long oil carbon chains (hydrocracking). These well-established processes can be used to treat vegetable oils and fats, such as oil seeds or algae rich in lipids, or residues as used cooking oil or animal tallow, or even co-products as crude tall oil from the paper making industry.

Oleochemical technologies, based on hydrotreating of lipidic feedstocks, are today performed by several oil companies (e.g. Neste Oil, Petrobras, ENI/UOP, UOP/Altair) to produce road HVO (Hydrotreated Vegetable Oils, also referred as Green Diesel) and aviation fuels (HEFA - Hydrotreated Esters of Fatty Acids). The current EU HVO technical production potential relies on a small number of plants, accounting for approximately 5 Mtonnes/y capacity. Among the current technological options for producing advanced biofuels by oleochemical technologies, the co-processing of biogenic liquid feedstock with fossil crude appears as a promising option. All these processes are hydrogen consuming and thus renewable hydrogen production can be considered a suitable option for greening the sector.

Despite current technologies are able to produce a high quality innovative set of fuels, the feedstocks utilized are still traditional. In recent years, microalgae have been considered a potentially interesting feedstock: a large number of scientific studies have demonstrated that the production of biofuels from microalgae is technically feasible, even if not optimized yet. Another alternative for lipid feedstock production is represented by the so called 'microbial oils', referring to oils derived from microbial conversion of sugar feedstocks.

1.1 Methodology

In this report, we focus on the state-of-the-art, ongoing R&D efforts, as well as future R&D needs of biochemical, thermochemical and oleochemical technologies to produce advanced biofuels for the transport sector from lignocellulosic biomass, waste oils/fats and algae. These technologies include: fermentation (cellulosic ethanol, higher alcohols, synthetic hydrocarbons, bio-jet fuel,); anaerobic digestion (AD) with pretreatment (biomethane from upgrading of biogas); gasification+Fischer Tropsch (BtL fuels); gasification+methanation (SNG); fast pyrolysis (bio-oil for upgrading); hydrothermal liquefaction (HTL, biocrude for upgrading); transesterification of residual/waste oil and fats (FAME); hydroprocessing of residual/waste oil and fats (HVO, Hydroprocessed Esters and Fatty Acids, HEFA).

The selection of advanced biofuels technologies has been made based on the basis of their technological readiness level. The sub-technologies covered in this report are characterized by a Technology Readiness Level (TRL)[1] of 4 or higher (pilot or demonstration stage). In

[1] The definition of TRL is given in the general guidelines of the Horizon 2020 Work Programme and guidance principles for specific renewable energy technologies are discussed in a recent report published by DG RTD (De Rose et al., 2017).

the last decade, these technologies received significant R&D funding (under the EU and international framework programmes) that have led to technical advances, but most of them are still characterized by challenges and barriers that will be discussed in the report. Hence, some of these technologies are still in the need for research and innovation support to improve their technical, economic and environmental performances, and give them the final push to achieve commercial status.

By searching for a combination of keywords[2] in the Community Research and Development Information Service (CORDIS)[3], for each selected sub-technology, we identified the relevant projects, funded under the Horizon 2020 programme (H2020) and carried out further analysis, in terms of objectives and main achievements in order to provide general considerations on their impact on the development of the technology. National projects and SET-Plan 'flagship projects/activities' provided by the Temporary Working Group (TWG) on the Implementation Plan for the SET-Plan Action 8 on Bioenergy and Renewable Fuels for Sustainable Transport' are also reported and included in the analysis. Flagship activities are defined in the Implementation Plan as "prominent ongoing R&I activities contributing to achieving the (SET Plan) targets and of interest to the public at large"; a flagship activity can be a project or programme with an innovation potential and the capacity to "lead by example" (Implementation Plan, Action 8, 2018).

The information on projects has been collected from CORDIS.

1.2 Data sources

The main data sources used in the analysis of the sector's **state-of the-art** and identification of pilot, demonstration and first-of-a-kind advanced biofuels plants were:

- The International Energy Agency (IEA) Bioenergy Task 39 '**Database** on facilities for the production of advanced liquid and gaseous biofuels for transport'. It contains relevant information on advanced biofuels projects that are being pursued worldwide by technology and technology readiness level (TRL);
- Other IEA Bioenergy Tasks, such as Task 33 'Gasification of Biomass and Waste', Task 34 'Direct Thermochemical Liquefaction' and Task 37 'Energy from Biogas';
- The European Technology and Innovation Platform Bioenergy (**ETIP Bioenergy**) website. The platform was launched in 2016 combining two previous initiatives: the European Biofuels Technology Platform (EBTP) and the European Industrial Initiative Bioenergy (EIBI). ETIP Bioenergy is an industry-led stakeholder platform that brings together relevant actors with the aim to develop sustainable and competitive bioenergy and biofuel technologies. It is recognized by the European Commission as the main interlocutor to implement the Strategic Energy Technology Plan (SET-Plan) in the field of biofuels and bioenergy (ETIP Bioenergy website).

The identification of sub-technologies status worldwide, as well as technical barriers and potential challenges to the large-scale deployment of advanced biofuels have also been based on major international studies, such as IRENA (the International Renewable Energy Agency), the IEA mentioned above as well as plants' websites and review papers.

[2] The used keywords are: biofuel, ethanol, biodiesel, lignocellulosic biomass conversion, gasification of biomass, syngas, fermentation, pyrolysis, thermochemical conversion, biomethane, Fisher Tropsch, hydrothermal liquefaction, transesterification, hydroprocessing, waste oil, aviation biofuel, hydrotreating, algae.

[3] Available at: https://cordis.europa.eu/ (accessed in January 2020).

2 Technology state of the art and development trends

2.1 Overview

This section provides an assessment of the state-of-the-art of advanced biofuels sub-technologies to convert lignocellulosic, non-food and non-feed biomass into liquid or gaseous biofuels for transportation.

As mentioned above, these include biochemical, thermochemical and oleochemical technology categories with varying maturity levels for which technical advances have been achieved in recent R&D efforts, although further research support is necessary to give them the final push to achieve commercial viability. The sub-technologies selected for this report are summarized in Table 1.

Table 1. Advanced biofuels sub-technologies

Sub-technology
Biochemical processes
Fermentation (cellulosic ethanol, higher alcohols, synthetic hydrocarbons, bio-jet fuel)
Anaerobic digestion (AD) with pretreatment (biomethane from upgrading of biogas)
Thermochemical processes
Gasification+Fisher Tropsch (BTL fuels)
Gasification+methanation (SNG)
Fast Pyrolysis
Hydrothermal liquefaction (HTL, biocrude)
Oleochemical processes
Transesterification of residual/waste oil and fats (FAME)
Hydroprocessing of residual/waste oil and fats (HVO, HEFA, renewable diesel, bio-jet fuel)

In the following section, for each sub-technology selected, we give an overview of major first-of-a-kind and demo plants that we could identify across EU (Table 2, Table 3, Table 4, Table 5). A comprehensive list of first-of-a-kind commercial plants outside EU is presented in Annex 1 (Table A 1, Table A 2, Table A 3).

A schematic overview of the technologies and the main process stages for each sub-technology is given in Figure 1 for biochemical processes, Figure 2 for thermochemical processes and Figure 3 for oleochemical processes.

Figure 1. Simplified biochemical process diagram for liquid and gaseous fuels production

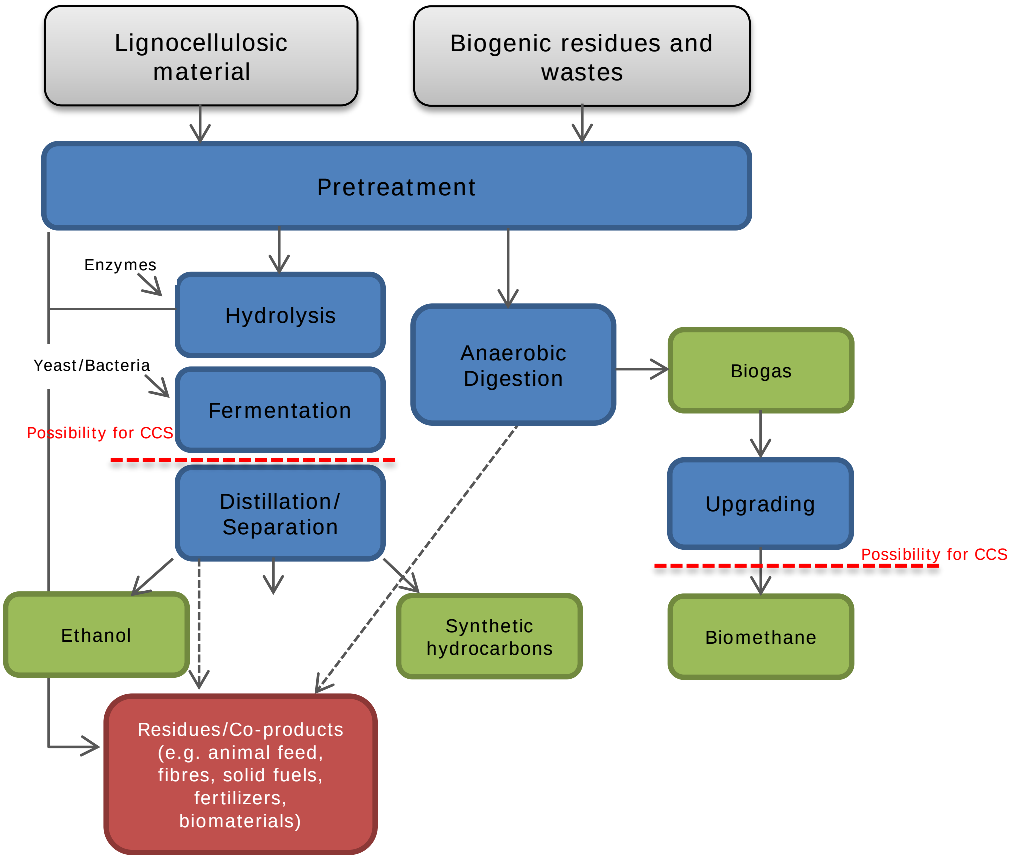


Figure 2. Simplified thermochemical process diagram for synthetic gaseous and liquid fuels production

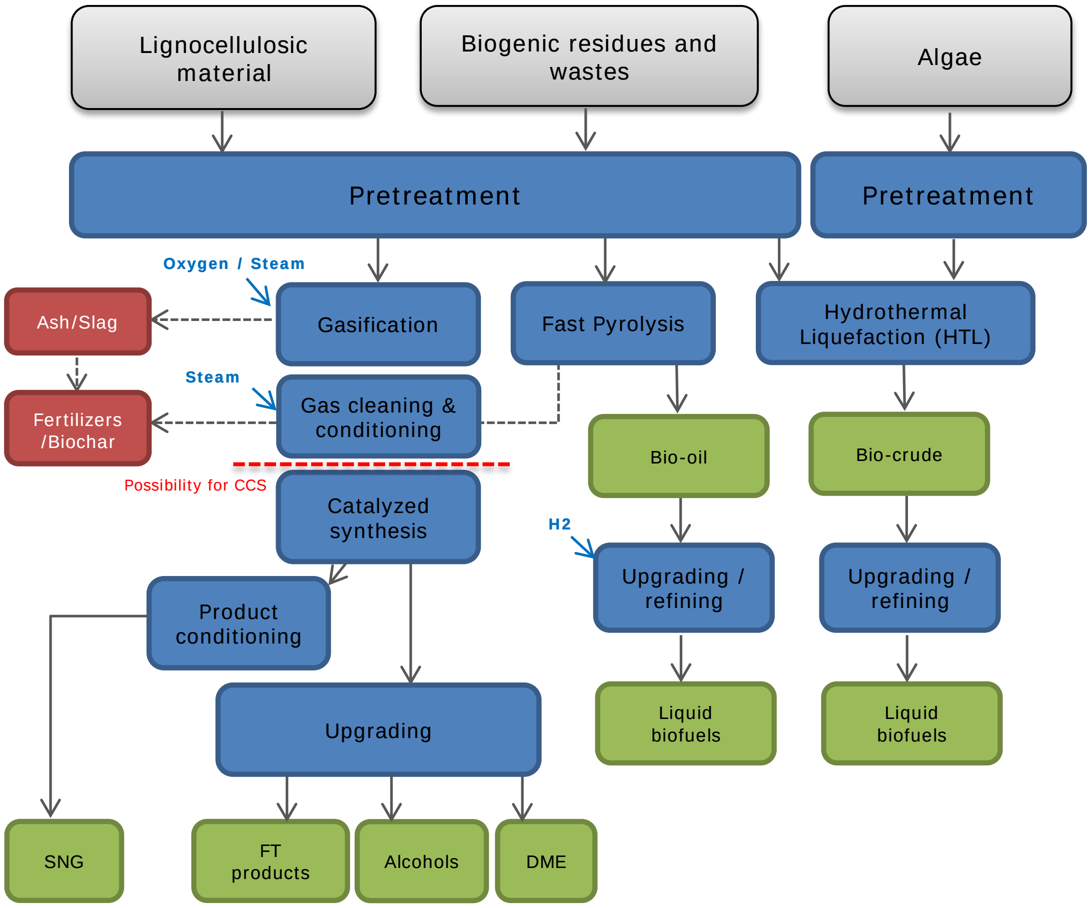
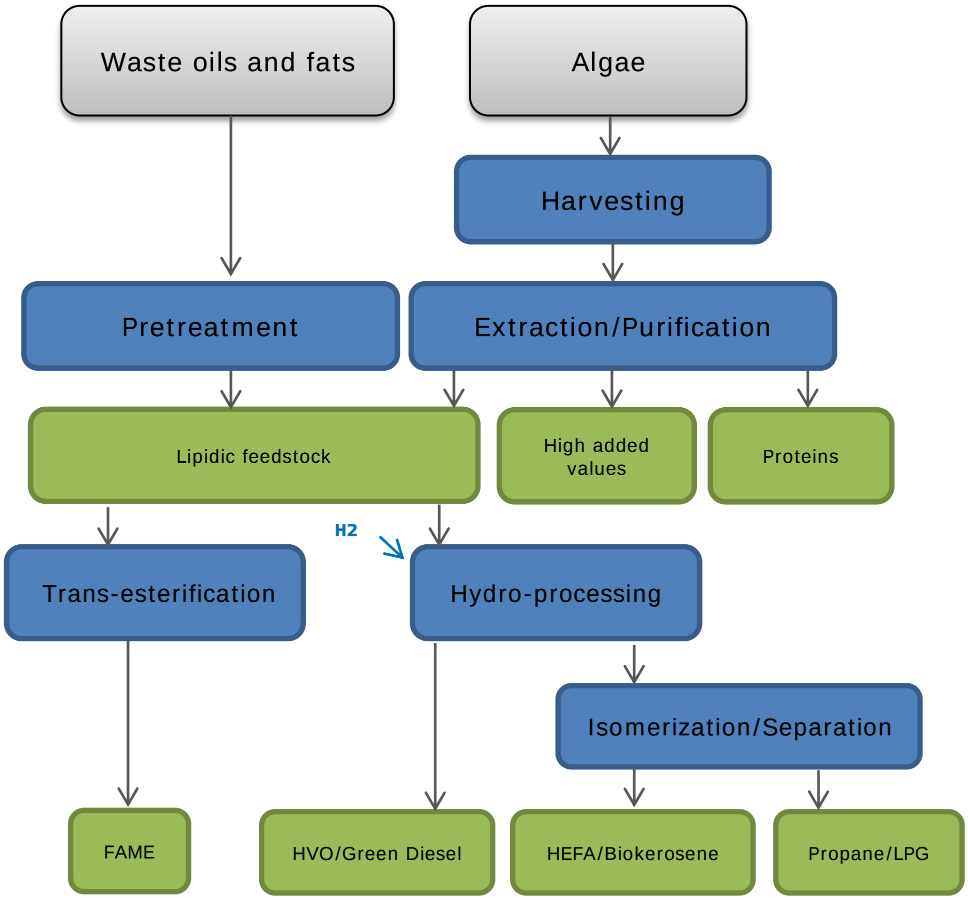


Figure 3. Simplified oleochemical process diagram for liquid fuels production



2.2 Biochemical technologies

2.2.1 Fermentation

Ethanol production from sugar and starch crops is a well-established technology. Ethanol production from cellulosic material is considered the most promising option for future fuel ethanol production.

While commercial size plants have been constructed in Europe, US and Brazil, regular and reliable production is yet to be proven. From that point of view, cellulosic ethanol production can be considered to be at TRL between 6 and 8.

The state-of-the-art of the main cellulosic ethanol production steps, i.e. **pretreatment**, **hydrolysis**, **fermentation and recovery**, is as follows. **Pretreatment** is crucial to ensure complete substrate utilisation. Within lignocellulosic biomass the carbohydrates are embedded in the complex lignin/carbohydrate structure of the fiber wall, which must be deconstructed. This is accomplished by mechanical, physical, chemical and/or thermal treatment of the substrate. Several pretreatment technologies have been developed, including steam explosion that is the most widely used pretreatment technology by industrial companies. However, the process needs a lot of energy and leads to the creation of byproducts that inhibit downstream fermentation (IRENA, 2016). Other pretreatment options include acid or alkali treatment, or solubilisation with solvents, e.g. the Organosolv process. Overall, this makes the use of special steels necessary. **Hydrolysis** of the liberated carbohydrates takes place using enzymes or dilute acid. Enzymatic hydrolysis is the most common route, although the high cost of enzymes currently represents a major contribution to the production costs (IRENA, 2016). Hydrolysis can also take place using strong acid processes or a combination of dilute acid followed by enzymatic treatment. These conversion processes need acid resistant steel reactors, Teflon or ceramics-coated materials (JRC, 2011). Acid hydrolysis leads to the creation of inhibitors with a negative impact on the fermentation process (IRENA, 2016). **Fermentation** converts the liberated sugars to biofuels using bacteria or yeasts (or other fungi). In fermentation processes a tight sterilisation scheme has to be applied making pressurised fermenter vessels and high volume flow-through autoclaves necessary. The biology and the process parameters have to be controlled frequently and to be kept within narrow ranges. **Recovery / extraction** of solvents is accomplished by the following methods: gas stripping, liquid-liquid extraction, evaporation, adsorption or membrane separation technology (JRC, 2011).

Globally, there are several first-of-a-kind commercial scale lignocellulosic ethanol plants, some of which are in the process of commissioning or ramping up to full scale operation. However, some of the plants are currently idle or on hold (see Table 2 and Table A 1 in Annex 1).

The actual cellulosic ethanol production to date has been markedly below the installed capacity, in part due to the use of innovative technologies, but also due to technical difficulties related to feeding, handling and processing large quantities of feedstock, high production costs and external factors such as low oil prices have also affected production (IRENA, 2016).

Expansion of cellulosic bioethanol production in EU is also restrained due to regulatory uncertainty. The EU28 annual production is estimated to be, in 2018, around 10 ktonnes that actually corresponds to the capacity of a single plant (USDA, 2019).

In US, the EPA's 2018 renewable fuel standard (RFS) data reports US biofuel production levels, and shows that in total, just about 30 ktonnes of cellulosic ethanol produced domestically in 2017 (US Energy Information Administration, 2018). Despite improvements in production, it is still uneconomic and not competitive with conventional ethanol production or fossil fuels without both plant construction and production being heavily subsidized (Rapier, 2018).

In EU, in 2019, no commercial scale plants appear to be in operation; two plants are on hold (one in Slovak Republic and one in Denmark) and one is idle (in Italy). Three plants are under construction or planned (two in Slovakia and one in Finland) (Table 2). One of the world's largest cellulosic ethanol production facilities, the Beta Renewables plant officially opened at Crescentino (Italy) in 2013 with a total capacity of 40 ktonnes per year. However, the plant has been shut down since October 2017 as a part of a restructuring effort of the parent chemical company Mossi & Ghisolfi (Lane, 2017). In 2018, Eni's chemical subsidiary Versalis acquired the Mossi Ghisolfi Group's green portfolio; an action plan to restart the activities of the Crescentino plant is under analysis (Padella et al., 2019).

Other projects have been announced for the production of cellulosic ethanol in the EU. The Cellunolix® project managed by St1 Biofuels Oy in cooperation with North European Bio Tech Oy, with an annual capacity of 40 ktonnes is planned to be operational in 2020 in Finland. This plant will use saw dust and recycled wood as feedstock and will be located at UPM's Alholma industrial area (USDA, 2019).

Enviral, the largest producer of bioethanol in Slovakia recently signed a license agreement to use Clariant's sunliquid technology and announced the construction of a new full scale commercial cellulosic ethanol plant integrated into the existing facilities at the Enviral's Leopoldov site (in Slovakia) producing 50 ktonnes/y of ethanol from agricultural residues. Clariant has also announced on-going construction of the first large-scale commercial Sunliquid® plant for the production of cellulosic ethanol in Romania (Clariant website).

Outside the EU, US and Brazil are attractive countries because of the availability of agricultural residues and the potential opportunity to either retrofit or expand existing ethanol production facilities to use lignocellulosic feedstocks (IRENA, 2016). There are four plants reported as operational producing cellulosic ethanol by fermentation: one in Norway, one in the **US** and two in Brazil (Table A 1 in Annex 1).

In US, POET-DSM Advanced Biofuels LLC inaugurated the cellulosic ethanol facility "Project Liberty" in August 2014 in Iowa. The plant has a production capacity of 75 ktonnes per year of cellulosic ethanol from corn stover and cob, and shares infrastructure with an adjacent ethanol plant. In summer 2017, the company installed a new pretreatment technology and announced the construction of an on-site enzyme manufacturing facility that will cut costs associated with the process (Schill and Bailey, 2017). Other plants in the US including Quad County Corn Processors adapted their conventional corn ethanol refineries to produce ethanol from corn kernel fiber, known as 1.5 generation technology. Even if the ethanol qualifies as cellulosic biofuel in US following the EPA definition, those plants should not be strictly considered as second generation ethanol production plants (Padella et al., 2019).

The 'Abengoa Bioenergy Biomass of Kansas' plant officially opened its commercial plant in October 2014 which was supposed to produce 75 ktonnes of cellulosic ethanol from a mixture of agricultural waste, non-feed energy crops and wood waste in Hugoton, Kansas (US). However, in December 2015, the plant ceased production due to financial difficulties and it is currently idle (IEA Task 39 Database). At the end of 2016, the cellulosic ethanol plant together with an integrated, co-located biomass-to-electric-power cogeneration plant has been sold to Synata Bio Inc. The company which has been formed in 2015 is based in Warrenville, Illinois and it is the one that acquired the assets to the old Coskata technology, a high efficiency gas-to-liquids technology (Lane, 2017; Schill and Bailey, 2017).

Brazil's first commercial-scale cellulosic ethanol plant (the GranBio plant) began production in September 2014, with current production capacity of about 65 ktonnes per year. The plant uses Beta Renewables PROESA technology. In 2015, production commenced at the Raízen Energia S/A commercial cellulosic ethanol plant at the Costa Pinto sugarcane mill. The 30 ktonnes plant uses technology developed by Iogen Energy, a joint venture of Raízen and Iogen Corp, to convert bagasse into ethanol (ETIP Bioenergy, 2018). Some production statistics indicate low but regular cellulosic ethanol production of around 20 ktonnes for 2018 in Brazil (USDA, 2018). There is large focus on producing ethanol in **China**, to meet their E10 blending mandate. Cellulosic ethanol production is forecast to stop at 20 million liters (or 16 kt) in 2018 as its major cellulosic project appears idle (USDA, 2018a). Their first cellulosic ethanol demonstration facility was built in 2012 by the Henan Tianguan company, and has a reported annual capacity of 10 ktonnes. Several larger (50 ktonnes per annum) cellulosic ethanol facilities are planned (USDA, 2018a).

Table 2. First-of-a-kind fermentation plants in Europe (TRL 8) (Padella et al., 2019)

Project owner - project name	Country	Feedstock	Conversion technology	Main Product	Output capacity (t/y)	Status	Start-up
Beta Renewables (acquired by Versalis) - IBP-Italian Bio Fuel	Italy	Lignocellulosic crops	Hydrolysis followed by fermentation	Ethanol	40 000	Idle	2013
Beta Renewables - Energochemica	Slovak Republic	Agricultural residues	Hydrolysis followed by fermentation	Ethanol	55 000	On hold	2017
Maabjerg Energy Concept Consortium - Flagship integrated biorefinery	Denmark	Plant dry matter, manure	Hydrolysis followed by fermentation	Ethanol	50 000	On hold	2018
Clariant - Clariant Romania	Romania	Agricultural residues	Hydrolysis followed by fermentation	Ethanol	50 000	Under construction	2020
St1 Biofuels Oy in cooperation with North European Bio Tech Oy - Cellunolix®	Finland	Saw dust and recycled wood	Reception of food waste (starch and sugar based feedstocks), hydrolysis of starches followed by fermentation	Ethanol	40 000	Planned	2020
Enviral – Clariant Slovakia	Slovak Republic	Agricultural residues (such as wheat straw and corn stover)	Hydrolysis followed by fermentation	Ethanol	50 000	Planned	2021

Several demo and pilot plants have also been constructed in EU and outside EU but most of them are currently idle or stopped while under construction. Few of them are reported as in operation in the IEA Task 39 database. They include: Clariant (sunliquid plant) in Germany, Chempolis Ltd. (Chempolis Biorefining Plant) in Finland and North European Oil Trade Oy (Ethanolix GOT) in Sweden with an annual capacity between 1 and 4 ktonnes of ethanol. The co-existence of pilot to flagship scale plants can be explained due to on-going efforts taking place to improve technologies and individual production chain steps, as well as successfully proving the overall chain performance at large-scale.

Syngas fermentation

Fermentation to ethanol or other alcohols (including butanol) can be also applied to **syngas** that is a biomass gasification-derived product further discussed in section 2.3 under thermochemical processes. Syngas fermentation combines approaches from the biochemical and thermochemical platforms and can be defined as a 'hybrid' route to advanced biofuels. Syngas may be fermented to ethanol (or other alcohols) using micro-organisms which act as biocatalysts including both aerobic and anaerobic species (such as the species Clostridia) (Karatzos et al., 2014).

Companies that have investigated or are developing proprietary fermentation organisms include Coskata, INEOS Bio and LanzaTech. However, Coskata that operated a demonstration facility in Pennsylvania (US) abandoned plans to scale up the biomass process and concentrated instead on natural gas opportunities (IRENA, 2016). INEOS Bio ended its cellulosic ethanol development and sold the Vero Beach, Florida (US) facility to Alliance Bio-Products, a subsidiary of Alliance Bioenergy in 2017. The company reported that the facility's biomass handling and back-end ethanol distillation units will be used, while the gasification unit will be replaced with Alliance's cellulose-to-sugar (CTS) reactor and the facility should be operational in 2018 (Schill and Bailey, 2017). LanzaTech developed a gas fermentation process to produce ethanol (and other chemicals) mainly from industrial waste gases (from coal-based steel mills) using proprietary microbes (IRENA, 2016). Therefore, their process will be further presented in the Advanced Alternative Fuel TDR report since their target market is non bio-based fuels. However, in the IEA Task 39 Database, it appears that Lanzatech has one operational demo plant in US (USA Mobile Demo Plant, TRL 6-7) that uses woody biomass syngas for the ethanol production.

Sugars to hydrocarbon fuels

Biological conversion can be also applied to sugars for direct conversion to hydrocarbon fuels using genetically modified yeast strains. This is an additional biochemical route able to produce finished fuels such as kerosene and diesel (including jet fuels) that can be easily integrated into current refuelling infrastructures. However, this technology seems to be using conventional sugar feedstocks rather than lignocellulosic feedstocks and significant development are still required to be compatible with advanced feedstocks (IRENA, 2016).

Amyris with Total use this technology to produce farnesene, which is then upgraded to jet fuel through hydroprocessing (IRENA, 2016) and there are 3 first-of-a-kind (TRL 8) operational plants (1 in US and 2 in Brazil) listed in the IEA Task 39 Database that are producing farnesene from sugar crops (mainly sugarcane).

2.2.2 Anaerobic Digestion (AD)

Anaerobic digestion (AD) is generally considered to be a mature technology for gaseous biofuel production. A review study based on Germany (Strzalka et al., 2017) indicates biogas and Organic Rankine Cycle (ORC) plants as the best-developed biomass-based renewable energy technologies, and this conclusion can be extended to a large part of EU28 initiatives (Billig and Thrän, 2016). In Europe, the number of biogas plants has grown at a regular pace in the last decade: in 2017, the European Biogas Association (Deremince, 2017; EBA, 2018) reported a total of 17 783 plants, of which 10 971 in Germany, 1 655 in Italy and 742 in France; for a total installed capacity of 10.53 GW. It is worth noticing that, unlike other renewable energy plants, biogas installations have reached high reliability and availability, allowing relevant energy production in term of kWh/y per installed kW. This relevant production potential has been developed for power generation, without heat recovery in most cases, mainly thanks to the supporting initiatives set at country level: feed-in tariffs (FITs), premium feed-in tariffs (FIP) and tenders (Del Rio et al., 2017).

The current general trend, at least for new installations, is to upgrade biogas to biomethane. The production of **biomethane** can ensure higher energetic conversion efficiency from feedstock to biofuel compared to the sole power production. The final cost of European biomethane is still not competitive with fossil natural gas, and countries (such as Italy (IT DM, 2018)) are supporting the sector with specific incentives. The key challenge is to improve economic performance by improving the efficiency and costs of the technology. Specifically, under past subsidies schemes, biogas producers have relied largely on food crops (especially maize) to maximize substrate supply and benefit from economies of scale. Most of the subsidy schemes in EU have now shifting in favour of higher support for the use of agricultural residues and organic fraction of municipal solid waste. While AD of manures and slurries is a well-proven technology, digestion of **ligno-cellulosic materials and MSW** has still technological barriers to overcome.

Feedstock **pretreatments** can be carried out using methods similar to those mentioned in the previous section for fermentation to biofuels. Mechanical, thermal, chemical and biological pretreatments are at various stages of development, particularly in Austria, Italy and Germany. Pretreatment also allows a wider range of feedstocks to be used in AD which can further reduce operating cost as well as reduce feedstock supply risk (see Figure 4). Lignocellulosic biomass requires delignification, and hemicellulose/cellulose hydrolysis, and alkali or biological pretreatments are today promising. Sewage sludge and waste activated sludge pretreatment has been already implemented at full-scale, mainly by using thermal pretreatment such as steam explosion. Another interesting waste stream for biogas is represented by fatty residues. In order to enhance their solubility and bioavailability, the saponification is typically the preferred technology. In the case of animal by-products, this pretreatment can be optimised to ensure sterilisation, solubilisation and to reduce inhibition linked to long chain fatty acids.

Figure 4. Technology readiness of various techniques for pre-treat biogas feedstock (Carrere et al., 2016)

Pretreatment / Feedstock	Mechanical	Thermal	Chemical	Biological
Sludge	Sonication High pressure Lysing centrifude Focused pulsed technique	Steam explosion Hydrothermal		
Animal by-products	Grinding	Hydrothermal Low temperature	Saponification	
Manure	Grinding Extrusion Maceration			Partial composting
	Nitrogen extraction			
Municipal solid waste	Grinding Maceration Extrusion	Steam explosion		Pre composting
Agricultural residues Energy crops	Grinding Extrusion		Alkali	Enzymes Ensiling Composting Fungi
Algae		Low temperature		

Full-scale application   Pilot-scale application   Promising lab-scale results

Improvements to AD process **monitoring and control** are also on-going and expected to increase output, reduce the cost of human input and reduce risks of process failure. While equipment for biogas upgrading to biomethane can be purchased commercially, there is still significant potential for **improving methane yield and reducing energy consumption** for either compressed or liquefied biomethane production for direct applications as transport fuel or for injection into the natural gas grid. A combination of careful **selection of feedstock and efficient process control** is now being tested in Germany and Denmark to assess the potential role of AD in both stabilising electricity grids and producing biomethane for storage (and possible transport use) at times of oversupply of wind and solar electricity. Research activities are also on-going on the side of a better digestate management; in particular, improving the value of this co-product by increasing its usability as fertilizer or to extract building-blocks for biomaterials.

As already mentioned, the AD sector is currently shifting toward the biogas upgrade to biomethane. Upgrading biogas to biomethane can be performed by means of various technologies, largely derived from other sectors (e.g. cryogenic separation of gases for medical and industrial sectors). These technologies include physical and chemical absorption, adsorption, membrane and cryogenic separations.

The technologies that are available today at industrial scale are:

- Pressure Swing Adsorption (PSA)
- Water scrubbing (WSC)
- Chemical scrubbing (CSC)
- Membrane separation (MEB)
- Cryogenic separation (CRY)
- A mix of the technologies.

Additional biological strategies can be considered as suitable for biogas upgrade but their level of maturity is lower compared to the ones mentioned above. Research efforts are being directed to the methanization of the CO_2 stream in order to increase the overall conversion of biomass to biomethane. Research is now focusing both on biological as well as chemical routes. For instance, methanation of biogas through bacteria is also considered as a promising option to maximize the gas yield and the achievable purity of the resulting biomethane. The idea is that the bacteria can produce biomethane using the carbon dioxide contained in the biogas together with renewable hydrogen. Several authors (Lee et al., 2012; Kougias et al., 2017) identify the potential of this pathway in the opportunity to produce hydrogen via water hydrolization by using power picks form wind and solar, thus acting as chemical storage. The process can be performed *in situ*, in which the H_2 is delivered inside the liquid phase of a biogas reactor to be coupled with the endogenous CO_2 or *ex-situ*, in which CO_2 and H_2 from external sources are injected into the reactor together with the liquid phase. The bio methanation efficiency can be equal or higher than 95% (Luo and Angelidaki, 2013). Despite the numerous advantages of biological techniques, practical challenges are limiting the market deployment; namely: high pH required, low gas-liquid mass transfer rate and consequent reactor dimensions and need for gas recirculation (Bassani et al., 2016). Such technology integration could represent a potential disruptive step towards the maximization of conversion efficiency of lignocellulosic feedstocks and increase the process competitiveness. The present challenge is to scale up these processes from laboratory scale to pilot and demo.

Technical availability, defined as the percentage of the operative hours with respect to the total annual hours, is a fundamental parameter for the separation step. Before being considered as ready for the market, a technology has to prove its performance, as the biogas plant itself has a significant availability but low possibility of biogas storage.

On the basis of available data from sector associations and literature sources (Hoyer et al., 2016; Angelidaki et al., 2018; IEA T37, 2016; Deremince, 2017; GIE and EBA, 2018; RBN, 2018 and DENA, 2018), JRC has conducted an analysis to try to characterise the currents state of EU AD sector; the derived dataset contains info related to plant location, feedstock used for biogas production, nominal productivity and technology used for biomethane separation. The data have been segmented in order to provide info on country technology penetration, typical technology as function of the nominal plant capacity, etc. According to JRC analysis, the total number of operative relevant plants is 465; in Figure 5, the number of plants per country has been reported as a percentage of the total EU28 plants. Germany is the country currently leading the sector, with more than 200 plants spread on its territory. UK, France and Sweden are also active in the field; surprisingly, despite the large number of biogas plants, Italy does not have a significant number of upgrading plants already in operation. Figure 6 shows the share of each technology reported as a percentage of the total EU28 plants; chemical scrubbing (CSC), water scrubbing (WSC) and Pressure Swing Absorption (PSA) represent more than 2/3 of the market. The market penetration of each technology is related to their capability of being scaled down compared to other commercial applications (e.g. production of liquid gases) (see Figure 7) to the typical size of biogas plants. Not surprisingly, WSC is the most flexible application, while the CRY technology suffers the poor economics of significant scaling–down.

Figure 5. Country segmentation on total EU plants

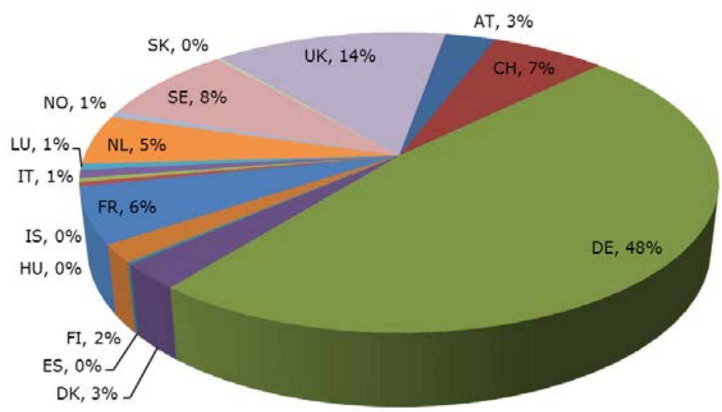


Figure 6. Percentage of technology penetration on the total current EU installed plants

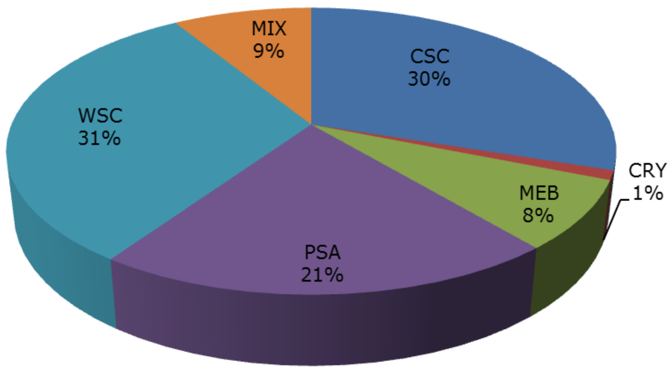
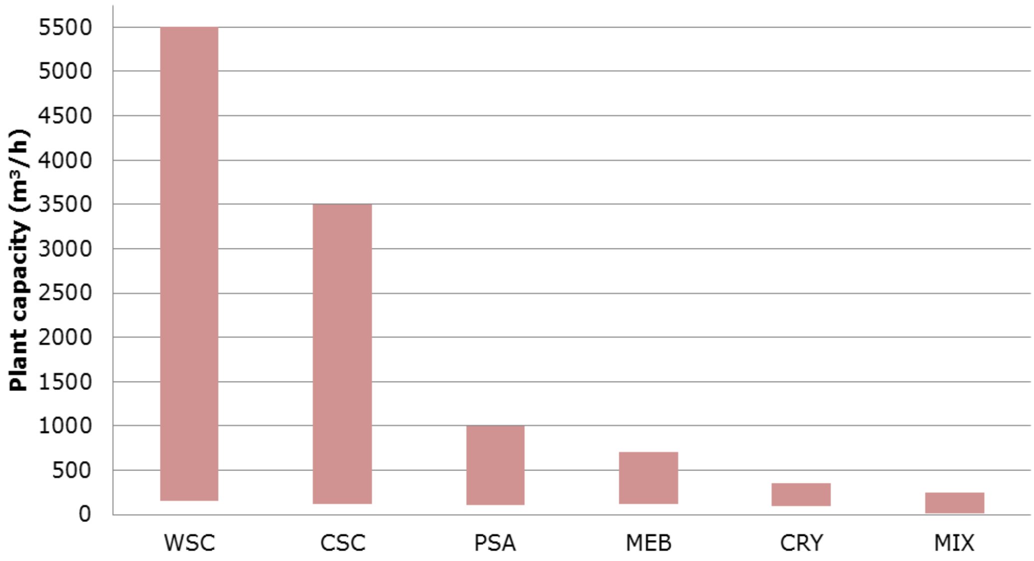


Figure 7. Typical range (max and min plant capacity) for each upgrading technology



On the basis of JRC analysis, the nominal capacity currently installed in EU28 accounts for 236 000 Nm^3/h. As the biogas plant availability (in terms of operational hours/y) has been proven to be very high and upgrading plants to biomethane is showing technical availability up to the 96% (Bauer et al., 2013), the annual potential energy output can be calculated on the basis of 8 410 h/y. The resulting annual nominal potential for biomethane can be estimated in 1 985 million Nm^3/y, equivalent to 71.66 PJ.

2.3 Thermochemical technologies

2.3.1 Gasification with Fisher-Tropsch (FT) for BtL production

A variety of synthetic gaseous and liquid fuels can be produced starting from gasification of ligno-cellulosic biomass feedstocks, as shown previously in Figure 2. **Gasification** is a high-temperature (700-1500 ºC) partial oxidation process (using one fifth to one third of the oxygen required for full combustion) through which biomass and a gasifying agent (air, oxygen or steam) is converted into synthesis gas, or syngas, principally CO and H_2. Minor amounts of solid char (or ash) and tars are also produced (IEA, 2014). Heat release from partial oxidation provides most of the energy needed to break the chemical bonds in the feedstock (NETL, 2018). Gasifiers can be classified by operating temperature, pressure, heat source (internal or external), and technology type (fixed-bed, fluidised-bed type etc). Most medium to larger scale biomass gasifiers are fluidized-bed type, while small-scale biomass gasifiers are fixed-bed downdraft type due to the low amount of tar they tend to produce (IEA, 2014b, Gasification Guide, 2010). Gasification process conditions can be designed to optimize the syngas quality needed; for the production of synthesis fuels, pressurized, **oxygen-blown gasifiers** are usually used. The use of air as a gasification agent is not favourable due to the resulting high N_2 content in the syngas (ETIP Bioenergy, 2018). Gasifier efficiencies can be compared by considering 'Cold Gas Efficiency' (CGE); the chemical energy in the product gas compared to the energy (LHV) contained in the feedstock. IEA report CGE's of 70–80% (IEA, 2014), but NREL (2012) are more conservative saying most commercial-scale gasification processes have CGEs of 65%, while some exceed 80%.

After gasification, **syngas must be cleaned** and conditioned before catalytic conversion. Along with CO and H_2, syngas contains CH_4, CO_2 and a range of higher condensable hydrocarbons (tars) & other pollutants, such as H_2S, particulate matter and nitrogen species. Cleaning requires high capital investments and subsequent steps of cooling and re-heating. It is necessary as the FT unit is extremely susceptible to impurities (Ail and Dasappa, 2016). The main processes needed in syngas cleaning are: - tar removal/cracking; - particulate matter removal; and - S, N, Cl species removal. Methods of syngas clean-up can be categorised into primary and secondary methods. Primary methods include modifying gasifier design, adjusting operating conditions (p, T, gasifying agent, residence time amongst others) and the use of in-bed catalysts and additives. Secondary methods concern physical processes (i.e. using cyclones, filters, electrostatic precipitators, scrubbers), and thermal-catalytic processes (thermal cracking, partial oxidation, catalytic reforming, plasma processes) (IEA, 2014c). Catalytic cracking of tar can be achieved partially in-situ via choice of bed materials but a specific additional reactor is needed to achieve the concentration limits required by downstream catalysts. Following syngas cleaning, the gas is **conditioned** to optimise its quality for catalytic synthesis. These steps may include the water-gas shift (WGS) reaction to ensure the desired H_2/CO ratio, steam reforming to convert larger hydrocarbons (such as methane) to additional syngas, and, possibly CO_2 removal if necessary.

Finally, a **catalytic synthesis** of the syngas to the desired product takes place. Products that can be obtained are: Synthetic Natural Gas (SNG) via methanation (see section 0), DME, methanol, H_2, synthetic diesel, jet fuel and synthetic ethanol. Production of Biomass-to-Liquid (BtL) is based on the **Fischer-Tropsch** (FT) conversion system, in which CO and H_2 gases react in the presence of a catalyst, to form liquid hydrocarbons. This is an established technology, and many components of the system are already proven and operational for decades in coal-to-liquid or gas-to-liquid plants. But the BtL process remains unproven at a commercial scale due to technical barriers as identified by Sims et al. (2010) which still need to be overcome. The main bottlenecks to BtL commercial penetration seem to be both technical and economical. Large scales are required to benefit from economies of scale both for the gasifier as well as the catalytic equipment, but this is often problematic for biomass installations due to biomass supply logistics. Further, efficient biomass pressurized gasification is still being investigated as well as hot syngas cleaning, specifically for efficient tar cracking and particulate removal at high temperatures.

In the EU, a number of demonstration projects have been planned and funded but never finalized (e.g. Choren in Germany, Solena in UK and more recently Kaidi in Finland). The companies claim unstable political support as the main reason cancelling the projects and progress has been hampered by bankruptcies in the sector. As shown in

Table 3, some projects are planned; they will operate using organic residues or waste streams and producing methanol or jet fuel components.

Outside the EU, there are a few BtL plants on a commercial scale: one operational in Canada and other plants under construction in the US which may become operational (see Table A 2). Most of the plants are operating or plan to operate with forest and agricultural residues, as well as post-sorted (after recycling and composting) municipal solid waste (MSW). Plant production capacities range between about 30 000 to 72 000 tonnes/year. There is a range of possible fuels which could be produced depending on reactor design and operating conditions. These include synthetic gasoline blendstocks and methanol.

Table 3. First-of-a-kind and demonstration BtL plants in Europe (TRL 8 and 9) (IEA Task 39 database)

Project owner - project name	Location and country	Feedstock	Main Product	Output capacity (t/y)	Status	Start-up
BioMCN – Woodspirit	Netherlands	Wood chips and glycerine	Methanol	413 000	On hold	NA
Rottneros AB - Vallvik Biorefinery	Sweden	Black liquor	Methanol	200 000	Idle	NA
VarmlandsMetanol AB - Vaermlandsmetanol Hagfors	Sweden	Forest residues	Methanol	130 000 m^3/y	Planned	-
Total – BioTFuel	France	Lignocellulosic material, i.e. agricultural by-products, forest waste and energy crops	FT-Diesel and Jet Fuel	Intend scale-up from pilot plant to industrial	Planned	2020
Enerkem and Suez - Ecoplanta Molecular Recycling Solutions	Spain	Organic residues and waste streams	Methanol	265 000	Planned	2022
Joint Venture of Air Liquide, Nouryon (formerly AkzoNobel Specialty Chemicals), Enerkem, Port of Rotterdam and Shell – W2C	Netherlands	Non-recyclable mixed waste, including unrecoverable plastic	Methanol	220 000	Planned	2022
Rottneros AB - Rottneros Biorefinery	Sweden	Woody biomass	Methanol	200 000	Planned	NA
Velocys - Altalto	UK	Municipal Solid Waste	Jet fuel component	58 000	Planned	NA

2.3.2 Gasification with methanation for SNG production

Synthetic natural gas (SNG) can be used to substitute fossil natural gas in industrial and household applications; efforts have been put in the last decade to produce SNG from solid feedstocks: coal and lignite, and plants are currently operating at commercial scale. In the same period, the possibility to feed these processes with biomass has been considered to bring new challenges for the technologies. Bio-SNG produced via gasification of cellulosic biomass, such as wood chips and forestry residues, could produce a valid, short term, drop-in carrier for existing infrastructures, such as vehicles and natural gas grid. Despite these advantages, supply methanation plants with biomass, instead of coal, is challenging due to the different composition of the organic feedstock. In order to produce SNG in a reliable manner, the biomass gasification step has to be properly tuned; the presence of tars can negatively influence the behaviour of the catalysts, which are a key part of the methanation stage. Additionally, the composition of biomass syngas, in term of CO, CO_2 and H_2 ratios, is typically not suitable for the process, and thus the use of steam gasification is required (Kopyscinski et al., 2010).

The biomass methanation has already been demonstrated at small scale. ECN developed a pilot technology for producing SNG from biomass gasification (ESME). ECN applies its own patented technologies (MILENA and OLGA) on a SNG pilot plant. ESME stage is designed especially for syngas from Bubbling Fluidized Beds, Circulating Fluidized Bed and allothermal gasifiers (e.g. ECN MILENA, TUV FICFB). The plant is a small-scale pilot: 3 KW fixed bed, filled with a commercial Ni-based catalyst (4 mm diameter x 5 mm). In 2015, ECN plant reached the 500 cumulated hours (Rabou & Almansa, 2015). Research activities will be directed towards the exploration of the operating limits, in order to enhance efficiency, increase throughput and/or improve catalyst lifetime.

Another interesting experience is the Center for Solar Energy and Hydrogen Research (ZSW), where the AER plant (Absorption Enhanced gasification/Reforming) has been developed. The plant uses a technology called "absorption-enhanced reforming (AER)", able to produce a hydrogen-rich product gas (H_2 content > $60_{vol.\%}$) to support the substitute natural gas stage. In the AER process, limestone particles act as natural fluidised bed material, which circulates between the gasification and the combustion reactor. The bed material transports heat from the combustion zone to the gasification zone, whereby the burnt limestone binds the CO_2 created in the gasification zone and has a catalytic effect on the gasification reactions. A reactive but stable bed material is of great importance for an efficient and secure gasification process. Important target values to be measured include the mechanical stability of the bed material, the material ageing, the CO_2 sorption behaviour and the catalytic activity (water gas shift reaction). Unfortunately, no updates on the project are available on literature or on the project website.

The Guessing gasifier operated from June 2003 to 2009, to carry on tests for the production of bio-SNG. The Fast Internally Circulating Fluidised Bed (FICFB) reactor allowed producing a very clean gas, suitable for being processed on the catalytic section of the methanation. The size of the SNG reactor was 1 MW. The first tests were successfully, also thanks to the cooperation with the Swiss Paul Scherer Institute (PSI). After long-term tests, some problems of catalysts deactivation were found. The batch of SNG produced in 2009 was sold to a car filling station for commercial demonstration. The positive experience of the demonstration plant in Güssing was used to lunch the GAYA project. Updates on the project show a relocation of the plant in Saint-Fons in Chemical Valley, south of Lyon, managed by ENGIE with the support of ADEME (the French agency for the environment and energy management) (ENGIE, 2018). The GAYA platform has been inaugurated in October 2017; their website reports: "Unlike first generation biomethane, which is now produced on an industrial scale, biomethane derived from dry biomass is still at an experiment stage" and no follow-up seems to be foreseen in the short-term. Other follow-up of Guessing plant are often claimed (i.e. Bioenergy2020+) but no reliable information has been found.

In 2014, the NER300 programme dedicated EUR 58.8 million funding to SNG project GoBiGas, located in Gothenburg (Sweden). Large-scale demonstration was supposed to be implemented in the second phase of the project from 2016. The plant aimed to demonstrate the conversion of low-quality wood into high quality SNG by indirect gasification at atmospheric pressure, gas cleaning, methane production via nickel catalyst, pressurization and injection of the product into the regional gas network. The plant used local forestry feedstock, including pulpwood and forest residues harvested from the surrounding areas of Gothenburg. The expected consumption was of 5 Mt/year of wet biomass to deliver about 50 ktonnes/y of SNG. According to the Board of Directors of Göteborg Energi, the project has been terminated in advance (BioEnergyInt, 2018), in a bid to reduce the financial impact of the plant (which was put up for sale in April 2017). Unfortunately, no other founder was found, and considering the financial impact of GoBiGas, the owner has decided to terminate the project in advance on March 28, 2018.

As shown in Table 4, Go Green Fuel ltd. had an initiative on the sector, but no recent updates have been found on their website (GoGreenFuel, 2018).

An on-going SET-Plan flagship initiative is the AMBIGO project, which aims to treat waste wood for producing 3 000 m^3/h of SNG from 10 000 tonnes of input. The installation is designed on an industrial scale. The partnership is composed of ECN, PDZN, DAHLMAN and recently GASUNIE and ENGIE joined the group. The start-up of the plant was foreseen for 2018. To date, according to the information from the official project website (https://www.ambigo.nl/en/timetable), no news about plant commissioning are reported.

Table 4. First-of-a-kind plants in Europe (TRL 8) (ETIP Bioenergy, 2018)

Project owner - project name	Country	Feedstock	Main Product	Output capacity	Status	Start-up
Go Green Fuels Ltd - Thermal Compressed Biomethane Plant	UK	Organic residues and waste streams (refuse derived fuel and waste wood, 7,500 t/y)	SNG	1 500 t/y	Under construction	Expected for 2018
Goteborg Energi AB - GoBiGas Phase 2	Sweden	Forest residues	SNG	160 GWh	Cancelled	NA
ECN - AMBIGO (SET-Plan flagship project)	Netherlands	Waste wood	SNG	300 m^3/h	On-going	Expected for 2018

2.3.3 Fast Pyrolysis & Thermo-Catalytic Reforming

Pyrolysis is the controlled thermal decomposition of biomass to produce oil, produce gas and charcoal/biochar. Fast Pyrolysis, and in particular Catalytic Fast Pyrolysis (CFP), maximises the production of bio-oil that can be considered as an intermediate for the production of drop-in biofuels. In principle, any dry biomass feedstock can be used as input but the composition of the feedstock will affect the yield and quality of the bio-oil. The oil characteristics are widely variable as function of the process used for its production; in general, pyrolysis oil can be described as a non-homogeneous brown liquid, with viscosity increasing over time, thus resulting in a limited shelf life. Bio-oil has also been referred to as pyrolysis oil, pyrolysis liquid, wood liquid, wood oil, liquid smoke etc.

Fast pyrolysis requires the rapid heating (high heating-rate) of small biomass particles (ca. 3 mm) to about 500 °C. Under these conditions the organic material decomposes, forming condensable vapours, permanent light gases and charcoal. The subsequent rapid cooling of the vapours to room temperature forms the liquid bio-oil product, within a share up to 75 wt.% yield. In order to maximize the liquid production, the biomass heating and vapour condensing rates need to be very high, at least 500 °C/s. Through this process, a more uniform stable and cleaner-burning product is obtained that can be used as an intermediate energy carrier and feedstock for subsequent processing. Key parameters affecting the yield and the quality of the bio-oil are biomass quality, process temperature and heating rate, vapours residence time, type of reactor and quenching time (IRENA, 2016).

Bio-oils produced from fast pyrolysis theoretically have a wide range of applications: they can be used to fuel stationary heat and power applications or being potentially upgraded to **drop-in biofuels**. The relatively high oxygen content of bio-oils affects the LHV (40% lower than fossil diesel) but can be tolerated for direct combustion in stationary power applications. Therefore, further extensive upgrading is required to produce deoxygenated hydrocarbon drop-in biofuel blendstocks. Upgrading bio-oil means treating it with hydrogen (e.g. by hydrocracking or hydrotreating) and/or through catalytic processes (e.g. zeolite cracking or fluid catalytic cracking) (IRENA, 2016). These processes used to upgrade bio-oils are similar to those used to upgrade vegetable oils to drop-in biofuels, although pyrolysis liquids are significantly more challenging feedstock to upgrade than vegetable oils.

The oil can be upgraded in a standalone plant or co-processed in existing crude oil refineries (co-processing). The advantage of standalone processes is that it can be optimised for the characteristics of the specific bio-oil, while co-processing in oil refineries can lower investment costs benefitting of existing processing capacity and economics of scale (IRENA, 2016).

The characteristics of bio-oil (highly acidic, high viscosity and high water content) make it difficult to be stored (with quality lowering with time), transported and downstream processed (Karatzos et al., 2014). Despite substantial research and commercial activities on pyrolysis over the last decades, current production capacity is very limited (IRENA, 2016).

Since the late 90s, a number of pilots, demonstration and semi-commercial plants bio-oil facilities have been built in EU, as well as in the US and Canada. However, despite these research and commercial efforts, current production capacity is still very limited and many projects and large scale installations ceased production due to poor economic and technical difficulties (e.g. Pyrogrot in Sweden, Dynamotive in Canada and KiOR in the US).

At present, there is a number of commercial and semi-commercial plants running in EU and outside EU (Table 5 and Table A 3 in Annex 1), producing bio-oil that can be upgraded to transport fuels.

Table 5. First-of-a kind fast-pyrolysis plants in Europe (TRL 8 and 9) (IEA Bioenergy Task 39 Database)

Project owner - project name	Country	Feedstock	Main Product	Output capacity (t/y)	Status	Start-up
Fortum/Valmet - Joensuu demo	Finland	Wood residues	Bio-oil	50 000	Operational	2013
BTG-BTL - EMPYRO project (part of Twence since December 2018)	Netherlands	Woody biomass	Bio-oil	24 000	Operational	2015
Green Fuel Nordic - Lieksa	Finland	Residues from forestry industry, such as sawdust and crown trunks	Bio-oil	24 000	Under construction	2020
Pyrocell (JV of Setra and Preem) - Pyrolysis oil upgrading	Sweden	Saw dust	Bio-oil	24 000	Under construction	2021

The Finnish company Fortum built, in November 2013, a “first of its kind" integrated bio-oil plant connected to the Joensuu power plant in Finland that produces electricity, district heat and 50 ktonnes of bio-oil/year using wood residues using VTT technology. The product is used as a substitute for heavy fuel oil, as well as raw material in the chemical industry, and it may be used for biofuel production in the future. In 2014, Fortum, in consortium with UPM and Valmet, announced a five-year project (LignoCat, lignocellulosic fuels) to develop and commercialize a technology to produce advanced lignocellulosic fuels by catalytic pyrolysis. However, no recent updates have been found on the project which appears to be a planned research project (TRL 1-3) in the IEA Task 39 Database. Another collaboration has been announced in April 2018 between Valmet, Fortum and a Swedish refinery company (Preem), to develop a technology for the production of transportation fuels. Valmet and Fortum's role is to develop and commercialize a technology similar to Fortum's Joensuu bio-oil plant for the production of upgraded bio-oil, while Preem will focus on processing the upgraded pyrolysis oil into transportation fuels. Commercial developments are expected by the end of 2020 (Valmet press release, 2018).

In 2015, the Dutch Biomass Technology Group BV (BTG) announced the operational start of the Empyro polygeneration pyrolysis plant to produce electricity, process steam and fuel oil from woody biomass. The core conversion process is a flash pyrolysis plant based on BTG technology. The Empyro project was financially supported by public (FP7 funding from the EC, the Dutch government and the province of Overijssel) and private funding. According to BTG-BTL website the Empyro plant has reached 100% of its nameplate capacity in October 2017 and in December 2018 Empyro became part of Twence. Both companies will work together on optimizing the plant and build an installation for the pretreatment of roadside grass as feedstock.

Other two projects were recently announced in Finland: one by Green Fuel Nordic (in March 2019) and the other one by Pyrocell. Green Fuel Nordic will build a fast pyrolysis plant using BTG-BTL technology with a similar capacity as the Empyro plant (Pyroknown website); Pyrocell, using sawmill residues from Setra Group's Kastet sawmill, will produce bio-oil (BTG-BTL technology) to be further processed into road transportation fuels at an the Preem's refinery (Sherrard, 2019).

Outside EU, the main commercialization efforts for biofuels production using pyrolysis were carried out in the **US** and **Canada**, but most of them were not successful.

The KiOR's plant in Mississippi was considered the world's first truly commercially catalytic pyrolysis facility producing biomass-derived drop-in biofuel and received USD 75 million loan from the State of Mississippi. However, since 2014, the facility is at idle and the company filed for bankruptcy in 2015 and fraud lawsuit has been initiated because of misleading claims about the company's achievements and capabilities (Ernsting, 2016).

As shown in Table A 3 in Annex 1, the only company in operation appears to be Ensyn (in Canada), which has more than 25 years of experience in producing bio-oils. Its core technology, the Rapid Thermal Processing (RTP™), converts non-food biomass from the forest and agricultural sectors to bio-liquids through fast pyrolysis. The Cote Nord Project appears to be in operation since 2018. The construction of a pyrolysis plant (Biozin biocrude) is planned in Norway for 2022.

Both inside and outside EU, there are also some demo and pilot plants for the production of transportation fuels with smaller capacities, which are not always reported in the IEA databases or in their websites. Some examples include: the Karlsruhe Institute of Technology (KIT) bioliq pilot plant in Germany producing around 600 tonnes/y of transport fuel, and partly financed by the German Agency for Renewable Resources; the bioCRACK project in Austria, a collaboration between BioEnergy International (BDI) and OMV, is a pilot plant for the production of synthetic fuels in operation since 2014 (see also section 4.2.4 on SET-Plan flagship activities). In US, Envergent, a joint venture between Honeywell's UOP and Ensyn, convert cellulosic biomass feedstock, usually forestry or agricultural residues into a liquid biofuel (Envergent website) using the rapid thermal processing technology.

Pyrolysis of algae

Recently, a continuous and increasing amount of research have been carried out on thermal treatment of microalgae (Pourkarimi et al., 2019; Khoo et al., 2019; Raheem et al., 2015; Chen et al, 2015; Silva et al., 2015; López-González et al., 2015; Na et al., 2015; Murata et al., 2015; Francavilla et al., 2015; Yuan et al., 2015). Pyrolysis of algae presents very different and peculiar characteristics compared to lignocellulosic biomass: these unique properties are reflected in the pyrolysis product itself. After the cultivation stage, microalgae are separated and then extensively dried (as required by the pyrolysis process). Pyrolysis oil and char are the main products recovered from the pyrolysis step, while the non-condensable gases can be used to provide heat to the thermochemical process as well as to dry the algae paste. Exhaust gases, recovered from the combustion of non-condensable, can be used to supply up to 10% w/w of the CO_2 needed by the microorganism during cultivation (without considering CO_2 distribution efficiencies). This scheme will process the whole algae stream, i.e. the entire alga composed by carbohydrates, proteins, lipids, and other remaining components as ash. An alternative route could be based on biomass fractionation just after the microalgae separation step. In this way, high added value products can be recovered from the algae stream, and then the remaining biomass/co-product can be fed to the pyrolyzer, after drying. Despite the number of efforts on using algae for pyrolysis, the major bottlenecks have been recognised in the overall energetic balance of the process, which results unsuitable due to high input for drying the feedstock.

Thermo-Catalytic Reforming

Thermo-Catalytic Reforming (TCR®) is a technology developed by Fraunhofer UMSICHT (a German industrial research organization) that combines intermediate pyrolysis with post catalytic reforming of the pyrolysis products (heating to 600-750 °C) in the complete absence of oxygen. Like regular pyrolysis, TCR produces a higher percentage of solid and gaseous products compared to fast pyrolysis (which principally produces liquid bio-oil).

There are two operational TCR units installed at Fraunhofer UMSICHT: a 2 kg/h bench scale reactor and a pilot scale 30 kg/h reactor that has been in operation since 2014. The scale up of the technology is one of the objectives of the H2020 project TO-SYN-FUEL.

Another H2020 project on TCR is the flexJET project which combines the TCR® technology for the production of biocrude oil from organic solid waste with SABR technology for the refining of biodiesel from organic waste fats for the production of a sustainable aviation fuel (SAF) (Benetti, 2018). This project is further described in section 4.3.1.

2.3.4 Hydrothermal liquefaction (HTL)

Unlike pyrolysis and gasification which use dry biomasses, HTL (also known as hydrous pyrolysis) involves processing wet biomass. It thus avoids highly-energy intensive feedstock thermal drying. HTL appears as a particularly promising conversion route for lignocellulosic feedstocks, MSW or other highly wet organic feedstocks, and macro- and microalgae. HTL involves directly liquefying biomass in the presence of water (and possibly a catalyst), to convert biomass into liquid oil, under pressure and with a reaction temperature of less than 400 °C. The high temperature of the water considerably increases its ability to act as a solvent (Zhang, Y., 2010). There have some been investigations of non-water solvents (PyNe, 2017). HTL yields a bio-oil product with an energy density generally of 30-36 MJ/kg, considerably higher than pyrolysis oil. HTL bio-oil (once of sufficient quality) can be co-processed with crude oil in existing refinery installations (Karatzos et al., 2014). Sauvanaud et al. (2018) in conjunction with Licella (more below), reported on successful co-processing of a 20% blend of HTL biocrude oil produced from pine chips and Straight Run Gas Oil (SRGO) to make road diesel. Regarding stability, the oxygen content of biomass results in biofuels with undesirably low chemical stability. But HTL produces an oil with a lower oxygen content than pyrolysis oils (Karatzos et al., 2014), and therefore could be seen as a more stable product. Indeed Lyckeskog (2016) found HTL bio-oil from lignin had good stability characteristics. The energy and GHG emissions performance of HTL systems mainly depends on the energy requirements for bio-oil upgrading. In addition, wastewater treatment should also be considered within the system boundaries for a proper assessment of the energy and GHG emissions balances, as well as the environmental impacts of the HTL process. Accurate assessments of GHG emissions from pilot plants operating in continuous mode is still lacking.

Production of renewable hydrocarbons via HTL is progressing; most HTL units are at the laboratory (TRL of 4) or pilot stage (TRL of 5-6), but other very recent projects appear to be close to commercialisation. Some researchers describe the production of HTL bio-oil as being slightly more advanced than the upgrading of the bio-oil (E4Tech, 2017). As far back as the 1980s, Shell Oil in the Netherlands built a large pilot HTL unit, fed by wet agricultural waste amounting to about 10 kg/h (dry basis), and had a capacity of about 560 litres of oil/day (Naber and Goudrian, 1997). It was discontinued and despite a Dutch consortium of Shell and other industrial partners restarting the process in 1997, this did not result further substantial development (Karatzos et al., 2014). In **Italy**, ENI use HTL at their 'Waste-to-Fuel' small-scale and discontinued pilot plant in Novara, using the organic fraction of municipal solid waste as feedstock. The first continuous pilot plant appears to be now operating at the bio-refinery in Gela: it can process about 700 kg of OFMSW per day, producing 70 litres of bio-oil, which can be used directly as a fuel or refined to obtain high-performance biofuels (Eni Website). In Italy, Biochemtex had planned under the RECORD project to produce HTL from the lignin by-product of cellulosic ethanol production, however this is likely not continuing. Other pilot plants are operational in **Denmark** (Aarhus University and Steeper Energy) according to the IEA Task 39 Database.

Licella, in **Australia,** have successfully tested different biomass feedstocks such as radiata pine, miscanthus and algae in HTL pilot plants. Their pilot facility has been scaled-up and could produce approximately 350 tonnes of bio-crude per year. Steps required for commercialisation noted in 2014 (Zhu et al) included process improvements to maximise bio-oil yield while minimising production costs. The technology now appears to be making a significant step towards commercialisation; in December 2017, it was confirmed Licella and Canfor Pulp a supplier of pulp and paper products had formed a joint-venture to integrate HTL technology into a paper mill in **Canada** (PyNe, 2017). A second project using the same technology, albeit focussed on waste plastic feedstocks is under development in the **UK** (Renew ELP, 2018).

In the **US**, Pacific Northwest National Laboratory (PNNL) of the US DOE has been involved in the implementation of continuous-flow HTL processing systems at the bench-scale to produce bio-oil from lignocellulosic materials and algae (more on HTL of algae in next section). Their results suggested HTL is a promising technology, but production costs were higher compared to petroleum-based gasoline. Costs reduction may be obtained with the minimization of organics losses to the water phase leading to improved yields of the final products and reduced wastewater treatment costs (Elliott et al, 2015).

In **New Zealand**, Christchurch company Solvent Rescue Ltd and their sister company Solray Systems developed HTL processes for producing oils from a range of biomass sources including algae, wood, wool-scouring waste and treated wood waste (Solray Energy, 2018).

Algae HTL

Considering the difficulties in extracting the lipids from microalgae, a possible alternative route is processing the whole algae stream (Chiaramonti et al, 2017). HTL is advantageous as it can directly convert wet biomasses into liquid bio crude (or solid bio coal at less severe pressure–temperature conditions) either with or without the use of a catalyst. After initial investigations many years ago, as reported in review works (Vardon et al., 2012), (López Barreiro et al., 2013), HTL began again to gain the attention of the researchers (Duan et al., 2011), when processing wet feedstock such as micro or macro algae (Guo et al., 2015), lignin from lignocellulosic ethanol production, organic wastes or other highly wet organic feedstock has become a very up-to-date issue (Xu et al., 2019; Li et al., 2019). Continuous-flow reactors showed yields of bio-crude equal to 35%wt (on a daf basis) for lignocellulosic feedstock; 27%wt daf for macroalgae and between 38-64%wt daf for microalgae (Wikberg et al., 2015). The HTL conversion efficiency of microalgae depends on various parameters such as reaction temperature, residence time and feedstock composition. Differently from the algae-to-biodiesel pathway, which essentially depends on the microalgae strain and lipid contents, HTL (and pyrolysis) can be used to convert not only the lipid fraction of microalgae, but also the other organic components such as proteins and carbohydrates, either as a whole or separated. The chemical properties of biocrude oil are directly related to feedstock composition (Costanzo et al., 2015). The typical HTL oil yield reported in several studies is equal to approximately 50–60% w/w (Biller & Ross, 2011), depending also on the use of homogeneous or heterogeneous catalysts. Most significant elements for the development of microalgae HTL processes are related to the feeding stage, especially in terms of aggregation state and load concentration, temperature, residence time, use of catalysts, product separation and water recirculation. A growing interest can be seen in the number of funded research projects and industrial initiatives that entered into operations in the last year, and the bio refining approach that is currently being promoted and combines high added value products with bioenergy components. Major studies carried out on the subject of microalgae HTL are (Patel et al., 2016; Faeth et al., 2013; Garcia Alba et al., 2012; Jazrawi et al., 2015; Roussis et al., 2012; Elliott et al., 2015).

2.4 Oleochemical technologies

2.4.1 Transesterification of residual / waste oil and fats

The most prevalent biofuel in the EU, with an annual production of approximately 10 million tonnes (USDA, 2019), is fatty acid methyl ester (FAME), historically referred to as biodiesel. EU FAME production could meet about 5% of the EU's annual road diesel demand of 185 million tonnes of diesel (USDA, 2019). FAME has been successfully produced industrially in the EU in significant volumes for over 20 years (Connemann and Fischer, 1998). It was principally made from vegetable oils in the past such as rapeseed, palm oil etc, but now there is growing focus on using waste or used cooking oils and animal fats. The amount of UCO and animal fats used to make biodiesel in the EU has increased considerably in recent years. Considering UCO alone, its use has gone from approx. 680 ktonnes used in 2011 (USDA, 2017) to an estimated 2.7 million tonnes in 2019 (USDA, 2019). There is a further 0.7 million tonnes of biofuel coming from acid oils and residues from the palm oil industry, but it is not clear if this is used to make FAME biodiesel or HVO, and importantly there is disagreement in the EU whether or not palm oil residues (specifically palm fatty acid distillate) which can be used as an animal feed additive should be described as waste. Nonetheless, Greenea (2019) estimated the total amount of waste-based biodiesel made in the EU that year would reach 3.3 million tonnes. FAME biodiesel is used as a blend component in standard European road diesel fuel (EN590). It is blended up to 7 vol% in EN590, and higher blending can occur though typically (in the EU at least[4]) under more restricted conditions. FAME has its own European standard for its use as a fuel, EN14214.

FAME conversion takes place by a chemical process known as transesterification. In transesterification, one ester (a triglyceride) is converted into another (a methyl-ester) in the presence of a base catalyst. The state of the art of the process typically involves **filtering / pre-treating** the feedstock to remove water and contaminants, and then **mixing with an alcohol** (usually methanol) and the **catalyst** (typically sodium or potassium hydroxides). This causes the oil molecules (triglycerides) to break apart and reform into methyl esters (biodiesel) and glycerol, which are then **separated** from each other and **purified**. The process also produces glycerine, which can be used as animal feed and a chemical feedstock, and also has many other small-scale uses. In addition to transesterification, free fatty acids which are not attached to a glycerol molecule and which can be prevalent in waste oil and fat feedstocks, can be **directly esterified** to methyl-ester using an acid catalyst and methanol in a process known as esterification. Methyl esters can be **blended** with conventional diesel or **used** as **pure** biodiesel. The use of bioethanol instead of (typically fossil) methanol to produce fatty acid ethyl ester (FAEE) has been investigated and could in theory reduce the GHG emissions of the fuel (Joanneum Research, 2016). FAEE is not commercially successful due mainly to the higher price of ethanol compared to methanol, and to additional technical difficulties compared to FAME production (Knothe et al., 2005). Unlike FAME, FAEE production does not have a European Standard (i.e. EN14214) which stops it being blended into standard fossil diesel (EN590), and is a considerable impediment to its large-scale use or trading as a stand-alone fuel.

In the EU, the industrial production of FAME is a mature technology, with an annual capacity over 21 million tonnes, and just under 190 factories in operation (Bockey, 2019) although the majority of facilities still use new vegetable oils feedstocks. There is not enough waste based feedstocks available in Europe; Greenea (2018) estimated the EU imports 50% of the UCO it needs to make UCOME, while indicating in 2019 that imports would need to further increase (Greenea, 2019). Significant FAME production in other parts of the world, mainly using new oil feedstocks, are: **South America** which produces 6 million tonnes annually, mainly in Argentina and Brazil, **North America** with 4.5 million tonnes mainly from the US, and **Asia's** 4.5 million tonnes coming from Indonesia followed by Malaysia (UFOP, 2016 and FAO, 2018). In **China**, there is limited government support for biodiesel and production appears low (less than 0.5 million tonnes per annum) (USDA,

[4] Infinium (https://www.infineuminsight.com/en-gb/articles/fuels/diesel-quality-trends-revealed/) note in South America FAME blends can reach 10 vol% and beyond in diesel fuel samples taken from the market

2017a), though production capacity is larger at close to approx. 5 million tonnes per annum (Tan, 2018). Exports are growing both of UCO and waste based biodiesel, due to demand in other regions (Greenea, 2018a).

FAME production has been running successfully industrially in various countries around the world for decades, but promising strategies to improve processing have been investigated. Heterogeneous (solid) catalysed production, as opposed to the homogeneous catalysis generally used to make FAME (and described earlier) has advantages; it needs no biodiesel water washing step, and separating biodiesel from glycerol is reported to be easier, but it brings the disadvantage of longer processing times (Saifuddin, 2015). Enzymatic and microwave assisted/ultrasonic catalysis, and supercritical processing (using high temperatures and pressures) have also been investigated. Enzymes convert FFAs which regular transesterification catalysts struggle with, and allows easy recovery of high purity glycerol. But it is seen to take place more slowly and at a higher cost than transesterification. Ultrasonic irradiation improves reaction characteristics by forming smaller droplets and improving mixing compared to traditional stirring methods, but it uses a large amount of catalyst which impacts downstream processing. Super critical method, in which the reaction mixture becomes homogeneous, no catalyst is needed, and transesterification of fats and esterification of FFAs take place simultaneously is promising, but the high temperatures and pressures needed mean it is not an industrial process, and it has been described as being in 'its infancy'. In addition the high temperatures can isomerise the methyl esters, reducing their fuel cold flow performance (Aransiola, 2014). Two other processing technologies, membrane technology (using membranes and chemical reactions), and reactive distillation which combines chemical and thermodynamic reactions have been researched to a much lesser extent. There have been investigations into improving the usage or value of the glycerine by-product, which could improve overall pathway economics. It could be used as a CHP fuel within the plant, or for example Succinity (2018) who produce succinic acid from glycerol and sugar, which can then be used to make bioplastics and solvents amongst other materials (Joanneum Research, 2016).

2.4.2 Hydroprocessing of residual/waste oil and fats

In the last decade, research has been performed by oleochemical companies to move from oxygenated biofuels (FAME) to drop-in advanced biofuels. Oleochemical lipid feedstocks upgraded to drop-in biofuel are generically referred as hydroprocessing, which consists of various catalytic reactions mechanisms in the presence of hydrogen (Vásquez et al., 2017). Saturating the double bonds present in a lipid molecule through catalytic addition of hydrogen is generally known as hydrogenation. Hydrogen addition in a catalytic reactor is also used to remove the carbonyl group after hydrogenation and, simultaneously, to break the glycerol compound, forming propane and chains of free fatty acids. The carboxylic acid group can be removed following three ways:

- hydrodeoxygenation (HDO), in which it reacts with hydrogen to produce a hydrocarbon with the same number of carbon atoms as the fatty acid chain and two moles of water;
- decarboxylation (DCOX), which yields a hydrocarbon with one carbon atom less than the fatty acid chain and a mole of CO_2;
- and decarbonylation (DCO) route, which also produces a hydrocarbon with one carbon atom less, as well as a mole of CO and water.

Alternatively, non-hydrogen processes can be used. In these pathways, a significant amount of carbon of the feedstock has to be oxidized, to produce the required hydrogen. However, these alternative routes to deoxygenation are generally less attractive as they can consume a significant amount of the feedstock.

Other downstream processes are required to improve biofuel combustion properties and meet the specification for the various sectors (e.g. aviation, etc.), namely: isomerization, cracking or cyclization (Al-sabawi & Chen, 2012). An example is HEFA-jet, which is co-produced with HVO-Diesel (or green diesel). The relative amounts of the various compounds (including water, gases such as H_2S, CO, CO_2, CH_4 and C_3H_8) are influenced by the operating conditions, including amongst others the catalyst used, the reaction temperature and pressure along with the feedstock type. Industrial optimization has been focusing on developing low cost, robust catalysts for treating complex blends of feedstock. Currently, the most successful catalysts are conventional bimetallic sulfide catalysts ($NiMoS_2$, $CoMoS_2$, and $NiWS_2$) supported on Al_2O_3 and monometallic catalysts, in particular Ni, Pd, Pt, Rh. As regards biojet production, DCO and DCOX reactions are recognised as being advantageous, as they can be performed at higher temperatures with a moderate acidic catalyst.

Europe is a world leader in HVO/HEFA production technologies, with several commercial-size plants currently in production. The current HVO and ASTM-compliant HEFA production potentials in the EU rely on a small number of plants (14), accounting for approximately 5 Mtonnes/y production capacity including so-called co-processing facilities; more in the following section (USDA, 2019). Lower production volumes can be expected for biojet considering that the majority of the technical potential is based on HVO plants, which have been designed and optimized for the production of road fuel and not aviation fuel. The current estimated maximum theoretical potential for biojet is therefore 829 ktonnes/y, in a strong biojet demand scenario. However, if HVO plants aim for maximum road Green Diesel potential and are not optimized for jet, an even lower figure can be considered: 355 ktonnes/y of biojet. By 2020, the situation may change significantly, with both the announced entry into service of new facilities, and the scaling-up of existing facilities in the EU (i.e. ENI, Total, etc.). For 2020-2025 the total production can be estimated at 3.3 Mtonnes/y, with an indicative average potential for biokerosene of about 0.5-1 Mtonnes/y.

Co-processing bio and fossil feedstocks

In addition to dedicated factories hydroprocessing vegetable oil feedstocks, another option, called co-processing, where fossil and bio-feedstocks are processed together in oil refineries, is being increasingly investigated. Thus, the capital costs of oleochemical processes could be reduced by leveraging existing process units, available in petroleum refineries. Hydroprocessing units situated at the end of the oil refining process are suitable for drop-in biofuel leveraging but the solution for inserting the bio feedstock is not entirely straight-forward. Moreover, the oxygen content of the lipid feedstock can cause corrosion and extensive coking of catalyst as well as downstream contamination risks: issues particularly sensitive for co-processing (ETIP Bioenergy, 2018).

TEXT BOX 1. Alternative feedstock: microalgae & microbial oils

The availability of sustainable feedstock for biofuel production is a clear need for the further development of the sector. Projects on microalgae as alternative feedstock for biofuels have demonstrated the technical feasibility, but the economic sustainability has not been achieved yet.

Among the main factors limiting the algae sector deployment, the most relevant ones are the biomass production and processing costs, mostly due to the complexity of the cultivation phase and the downstream processes required to extract the high-value products in a biorefinery concept. Despite these critical issues, algae biofuels are particularly attractive because of the following major elements: (i) algae can be produced on marginal or degraded lands, avoiding competition with traditional food crops; (ii) algae are able to accumulate significant amounts of lipids (for biodiesel, HVO, and other processes) or carbohydrates (for bioethanol); (iii) algae can be grown without pesticides or herbicides; (iv) algae can grow in saline waters, thus without depleting fresh water resources; (v) algae can use carbon from flue gases; (vi) algae can be cultivated on wastewaters, where they can also find part of those nutrients needed to grow (Wijffels et al., 2010).

Despite the high biomass production of microalgae per unit of land (t ha^{-1}), the energetic consumption for biofuels production, including harvesting and extraction, is still a limiting factor.

Algae harvesting is estimated to be responsible for a significant share of energy consumption, up to 20–30% of the total production cost (Barros et al., 2014). Downstream processing must separate very small cells from a cultivation medium characterized by a very low density (from 0.5 to 3 gr/l).

In a lipid-based approach toward diesel-like biofuels, specific cultivation techniques, such as Nitrogen and Phosphorous starvation, can improve the oil quantity and quality. Algae can accumulate neutral lipids up to 50% of the dry biomass, with triglycerides representing the most abundant component (Stephenson et al., 2010; Bondioli et al., 2012).

However, lipids contained in microalgae are intracellular: this makes the oil extraction significantly more complex than the extraction from conventional oil seeds; in fact, mechanical pressing is not applicable to microalgae (Dejoye Tanzi et al., 2013). After harvesting, the algae paste still contains more than 80% water (on wet basis): this is a key element for the selection of the following downstream processing methods.

Wet extraction can be considered in order to avoid biomass drying and therefore save energy, improving the overall sustainability (Chiaramonti et al., 2017).

However, dry extraction routes are today the more mature technologically options. Moreover, they separate the protein-rich cake, a high added value co-product that contributes to improve the economic performances of the chain.

Solvent extraction is the most common method used to extract lipids from oily seeds: the efficiency of the solvent extraction process is strongly dependent on the specific algae strain under consideration (Grima et al., 2013).

Among the biological extraction methods, enzymatic extraction degrades the cell wall, with relevant energy saving (Taher et al., 2014); the critical element of this method is represented by the cost of enzymes.

There is no general optimal solution for algae harvesting and downstream processing, as each algae strain and product destination can require different technical setting (Sanders et al., 2010; Pragya et al., 2013).

Currently, the conversion of algae to sustainable biofuels has not reached commercial scale, despite the large potential offered by the algal feedstock and the existence of large demo plants (i.e. Caporosso BIOFAT facility, ALL-GAS facility etc. (ETIP Bioenergy, 2018)).

Research on microalgae is currently oriented to the accumulation and extraction of high added values molecules (i.e. omega-3 like DHA and EPA, PUFA, carotenoids, etc.) and proteins, and the new paradigm seems to be considering the lipid fraction as a co-product instead of as the main target of the production. This approach may lead to a reduction in algae oil cost, by means of an improved economical balance of the biorefinery. Nevertheless, the different scale of these markets (e.g. nutraceutical and pharmaceutical) does not guarantee a proper sizing of the plants for lipid production, when targeting typical demand size from the biofuel sector.

Another alternative for lipid feedstock production is represented by the so-called 'microbial oils'. The term "microbial oil" has been typically used to refer to oils derived from microbial sources, also named unicellular oils or single-cell oils (SCO) (Sabikhi & Kumar, 2012). With few exceptions, oleaginous microorganisms are eukaryotes, including algae, yeasts, and molds (Hammond & Glatz, 1988). For some authors the maximum lipid yield (total lipids, thus not only vegetable oil) is equivalent to about 50% of dry biomass (Ratledge, 2004), while others claim higher yields for yeasts: such as *Candida curvata*, *Trichosporon cutaneum*, *Rhodosporidium toruloides*, and *Lipomyces starkeyi,* which are expected to store even larger quantities of lipids (up to 70%, w/w). Theoretically, these figures represent a great potential for the biodiesel (HVO and HEFA) sector but high manufacturing costs is today limiting their use as feedstocks for biofuels (Anschau, 2017; Ratledge & Cohen, 2008). Differently from algae cultivated in autotrophic conditions, the main source of cost for microbial oils production is the carbon feedstock, typically glucose. Currently, oils from plants and animals cost in the range of EUR 0.40 – 1.50 /kg, whereas microbial oils costs are reported to be significantly higher (> EUR 100 /kg) (Wynn et al., 2010).

2.5 Trends in biofuels patents

For the purpose of providing an assessment of the inventive activities related to advanced biofuels technologies, we analysed the trend in the total number as well as the world distribution of patent filings in the time period 2000 and 2016 as extracted from PATSTAT database 2019 (JRC based on data from the European Patent Office (EPO), 2019; Pasimeni, 2019; Pasimeni et al., 2019)[5]. The year 2016 is the latest complete available year due to the length of the patenting process as a consequence of confidentiality and property rights (Fiorini et al., 2017). Only incomplete (typically lower) figures are available for 2017 onwards, which therefore do not accurately represent the patenting activity on biofuels and are not reported in the following graphs. Likewise, the patent activity beyond 2016 cannot be extrapolated from the curves trends as major R&I activities were supported at least under the European Framework Programme Horizon 2020, illustrated in Section 3 below.

The Cooperative Patent Classification (CPC)[6] and, specifically, the Y codes which are designed to facilitate the identification of inventions relevant to renewable energy and climate mitigation technologies were used. Within this classification, the set of technical classes of inventions that can be related to the advanced biofuels technologies, are patent families with code Y02E 50 that include CPC classes referred as 'technologies for the production of fuel of non-fossil origin'. From this broad category, we selected the sub-categories referring to 'biofuels' and 'fuel from waste' trying to identify the technologies described in the frame of our report and ignoring the ones that are not relevant or part of other technology reports (such as torrefaction of biomass, grain bio-ethanol and methane from landfill gas). However, it should be noted that the selected CPC classes are quite broad and may still include a range of biomass-based process technologies that do not strictly relate to the advanced biofuels technologies. For example, 'fuel from waste' classes may focus on many aspects of thermal treatment and disposal of MSW, sludge and industrial wastes that apply across conventional and/or advanced biofuels technologies for power generation and/or transportation fuels sectors. Similarly, it cannot be excluded that the biofuels and biodiesel classes consider the patenting activities also pertaining food-

[5] Possible differences with data reported in the previous report (2018) are due to improvement in the JRC data processing of the raw patent dataset provided by EPO. This process increases data coverage, particularly for Asian countries that are often associated with incorrect or missing country codes, because of the incomplete provision of information from the national patent authorities. Furthermore, periodic revisions of the PATSTAT database run by the EPO (i.e. technological reclassification of patent applications or addition of new attributes to patent applicants) could potentially have an effect on the consistency and reproducibility of time series based on subsequent database versions.

[6] Information on the CPC codes can be found at:
http://www.cooperativepatentclassification.org/cpcSchemeAndDefinitions/table.html

crops derived biofuels that, by definition, should not be part of the advanced biofuels categories. Therefore, it is not always possible to strictly relate the inventions activities of CPC class with a specific advanced biofuels technology, while only general considerations can be drawn on this field. The sub-categories included in the analysis are shown in Table 6. Biofuels such as biokerosene or pathways such as SNG from gasification which do not seem to appear as a specific CPC class should be considered as part of the category 'Biofuels (not classified elsewhere)'.

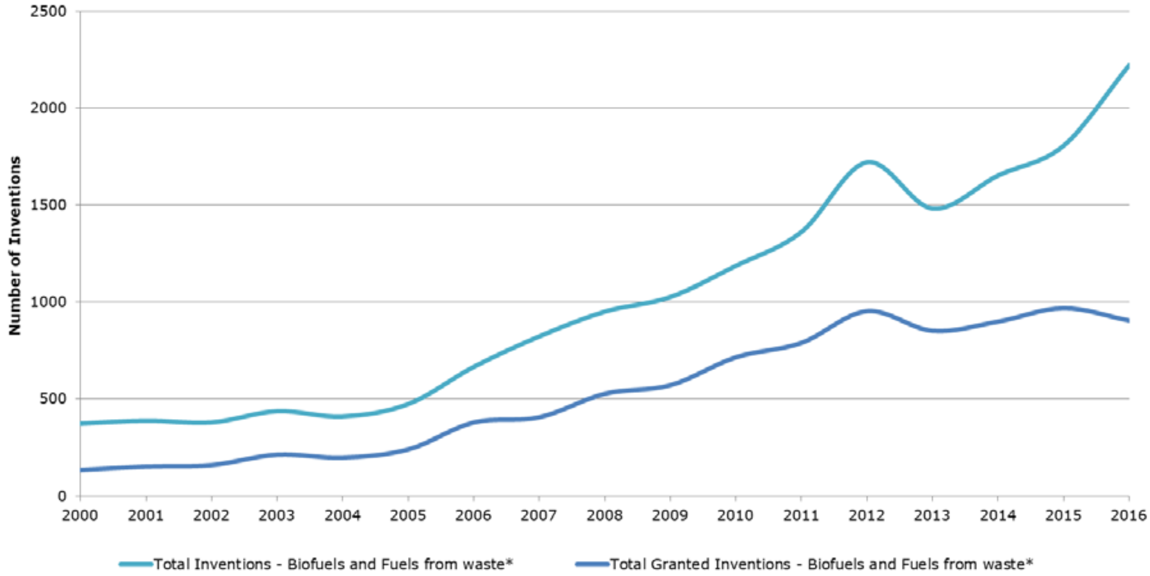
Table 6. Code and names of selected CPC classes related to biofuels technologies

CPC code	CPC name
Biofuels	
Y02E 50/10	Biofuels (not classified elsewhere)
Y02E 50/11	Biofuels - CHP turbines for biofeed
Y02E 50/12	Biofuels - Gas turbines for biofeed
Y02E 50/13	Biofuels - Bio-diesel
Y02E 50/14	Biofuels - Bio-pyrolysis
Y02E 50/16	Biofuels - Cellulosic bio-ethanol
Y02E 50/18	Biofuels - Bio-alcohols not produced by fermentation
Fuels from waste	
Y02E 50/30	Fuel from waste (not classified elsewhere)
Y02E 50/32	Fuel from waste - Synthesis of alcohols or diesel from waste including a pyrolysis and/or gasification step
Y02E 50/343	Fuel from waste - Methane production by fermentation of organic by-products

Patent statistics are related to the number of patents based on the priority date (first filing date) between 2000 and 2016. Note that in case of CPC codes, each patent family (invention) can be associated with more than one code. In order to estimate the share in total inventions a fractional count should be adopted, where inventions tagged with more than one code contribute with an equal fraction to all the codes (classes) involved. Additional information on the methodology used to compile the patent statistics is available in Fiorini et al., 2017; Pasimeni, 2019 and Pasimeni et al., 2019.

Figure 8 shows the trends of the total and granted world inventions in 'biofuels' and 'fuel from waste' (excluding torrefaction, grain bioethanol and methane from landfill gas as explained above) between 2000 and 2016. The world patenting activity in 'biofuel' and 'fuels from waste' registered a very significant increase from 2004 to 2016 with a decline only in 2013.

Figure 8. Trend of total and granted world inventions in 'Biofuels' and 'Fuel from waste' CPC classes (excluding torrefaction, grain bioethanol and methane production from landfill gas)



* excluding Y02E 50/15-Torrefaction of biomass, Y02E 50/17-Grain bioethanol and Y02E 50/346-Methane production from landfill gas

Figure 9 presents the number of granted inventions financed by the public or private sector during 2000-2016 in the world and in the EU. Private funding is steadily higher than public funding in the considered time period. World inventions financed by public funding reached the maximum number in 2013. In EU, the peak was reached in 2012 for both public and private funding. This peak and the general trend could be explained by a number of factors including the economic crisis, the approval of the Renewable Energy Directive in 2009 and the debate on the indirect land use change (ILUC) impact which greatly affected first generation biofuels. Figure 10 shows the trend of granted inventions financed by the public or private sector in China and US.

Figure 9. Trend of granted inventions in 'Biofuels' and 'Fuel from waste' CPC classes (excluding torrefaction, grain bioethanol and methane production from landfill gas) financed by public or private sector

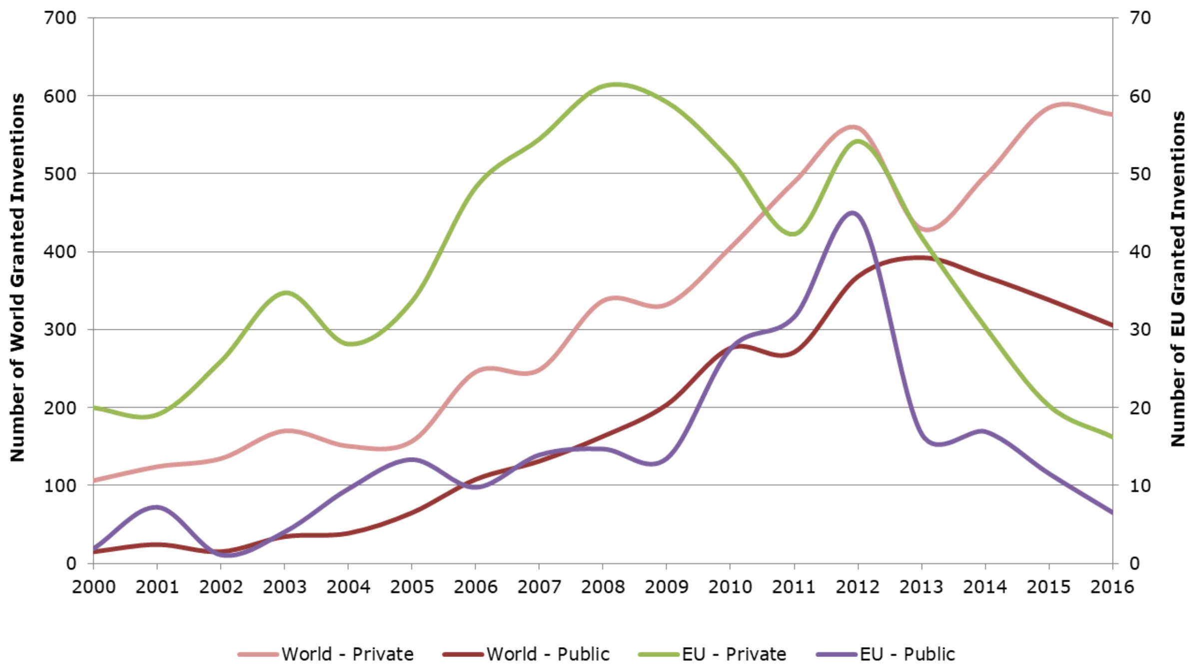


Figure 10. Trend of granted inventions in 'Biofuels' and 'Fuel from waste' CPC classes (excluding torrefaction, grain bioethanol and methane production from landfill gas) financed by public or private sector in China and US

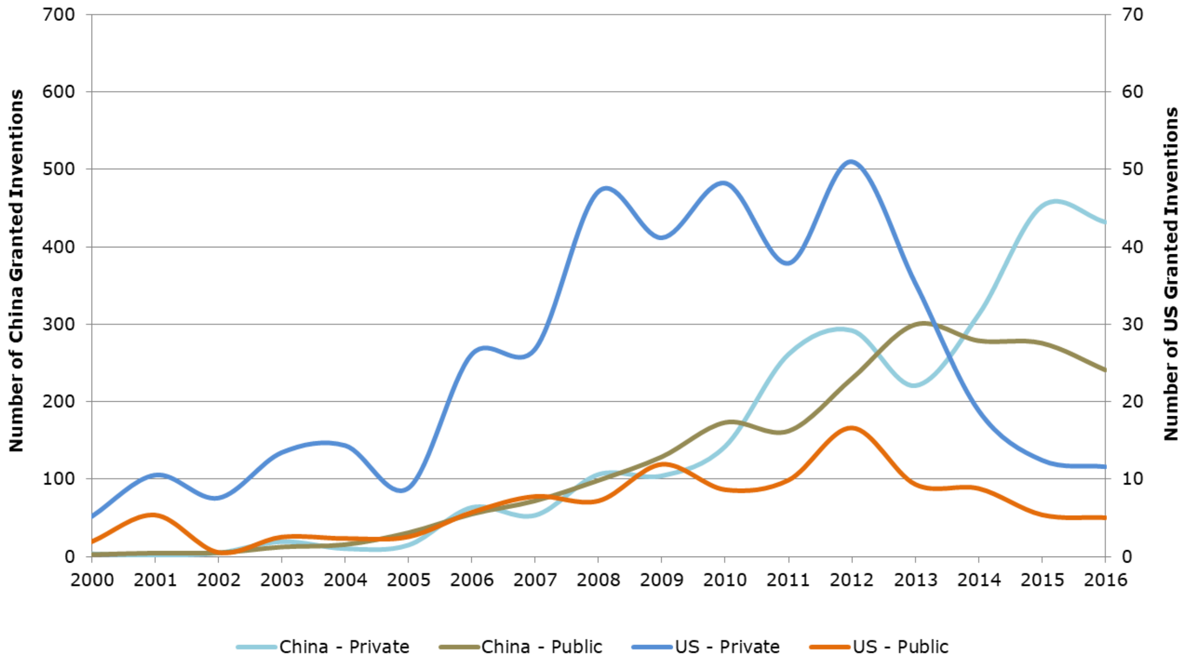


Figure 11 shows the trends in the selected CPC sub-classes for the same years, while Figure 12 displays the share of the CPC sub-classes over the total number of granted inventions in the same time period.

Among the sub-classes, the highest number of granted inventions was found for 'fuel from waste-methane production by fermentation of organic by-products' (Y02E 50/343), which represents more than 40% of the total granted inventions on the biofuel technologies for the considered time period. The patenting activity in 'biofuels-biodiesel' (Y02E 50/13) increased until 2012, but started to decline afterwards. It represents 13% of the invention activities occurred between 2000 and 2016. Similarly, the patenting trend for 'cellulosic bioethanol' (Y02E 50/16), that counts for 13% of the total granted invention between 2000 and 2016, showed a sharp increase between 2005 and 2008, but decreased after 2012. An increase in the number of granted patents occurred for bio-pyrolysis technologies (Y02E 50/14) between 2004 and 2015 (Figure 11). Bio-pyrolysis represents 13% of the total granted inventions between 2000 and 2016.

Figure 11. Trend of world granted inventions activities by CPC classes

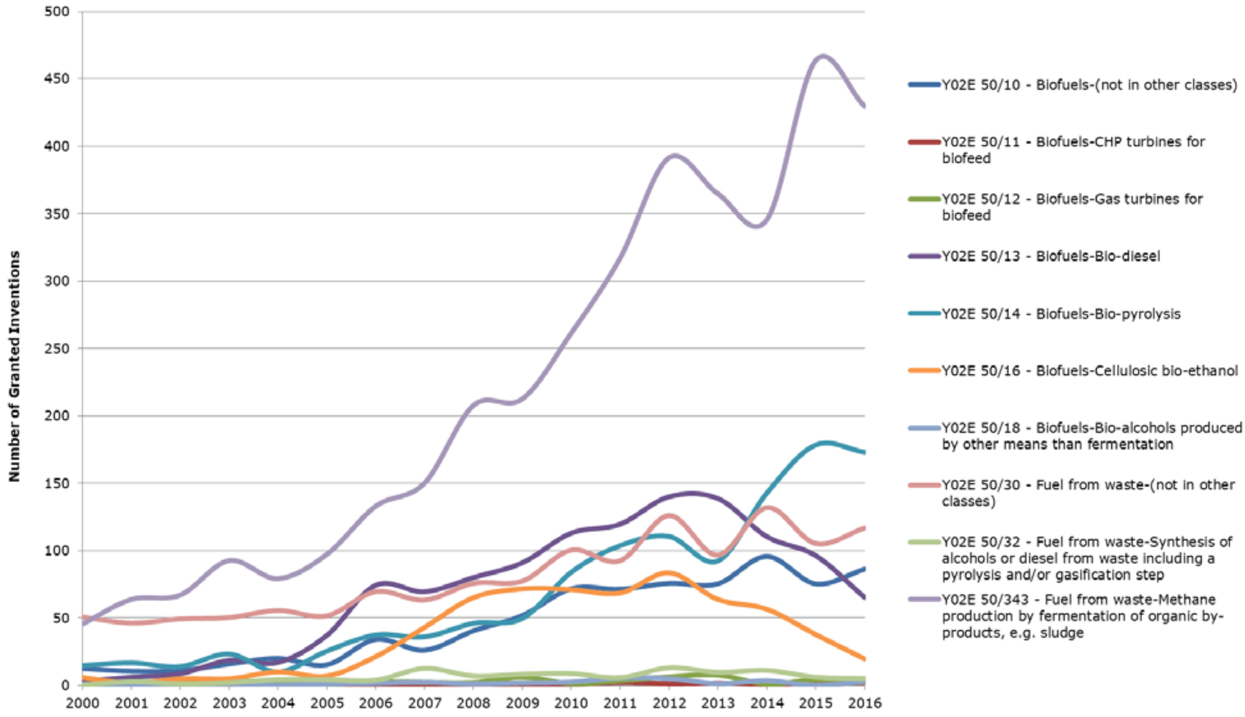


Figure 12. Shares of CPC sub-classes over the total granted inventions (2000-2016)

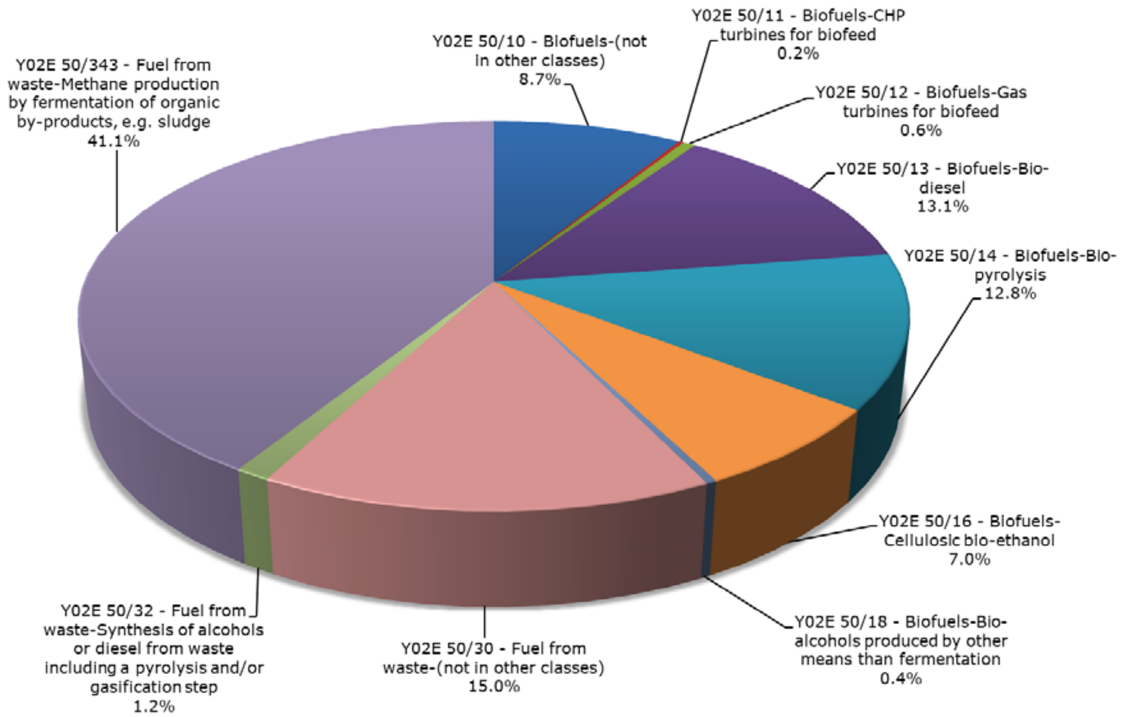


Figure 13 shows the share of granted inventions on biofuel technologies in the two CPC classes ‘biofuels’ and ‘fuel from waste’ (excluding torrefaction, grain bioethanol and methane from landfill gas) by world countries/regions between 2000 and 2016 (on the left side) and in 2016 (on the right side). China is the country where the highest number of inventions was found with a share of more than 50% of granted inventions in the considered time period, followed by Japan (14%), EU (11%) and Korea (11%). In 2016, China’s share is even larger (76%) and it appears to be the only country where the number of granted inventions had increased since 2004 (Figure 14). However, Figure 15 shows that the number of high value inventions is constantly higher in the EU compared to any other country in the world.

Figure 13. Share of granted invention activities in ‘Biofuels’ and ‘Fuel from waste’ CPC classes (excluding torrefaction, grain bioethanol and methane production from landfill gas) by world player in 2000-2016 (left) and in 2016 (right)

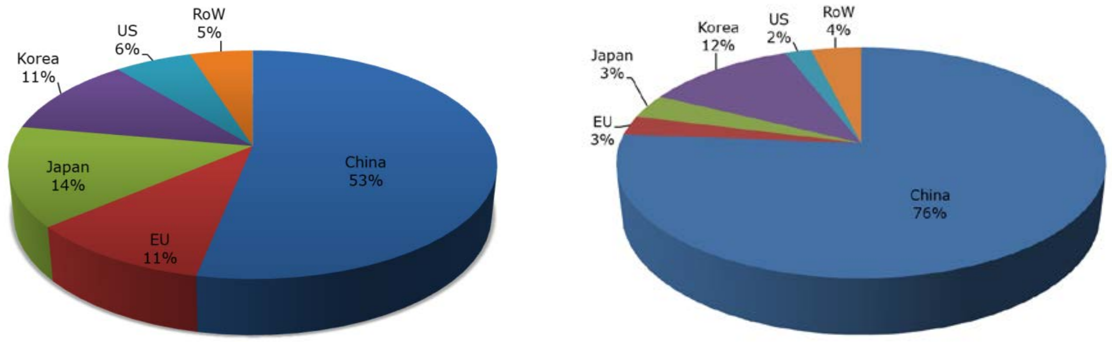


Figure 14. Trend of granted invention in Biofuels' and 'Fuel from waste' CPC classes (excluding torrefaction, grain bioethanol and methane production from landfill gas) by world player and year

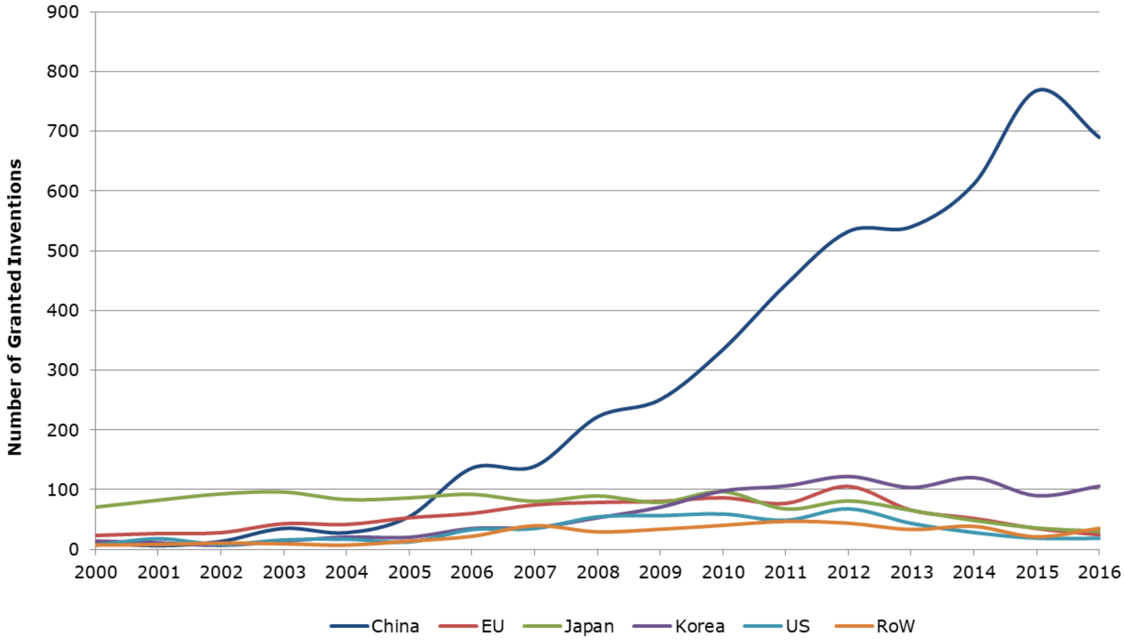
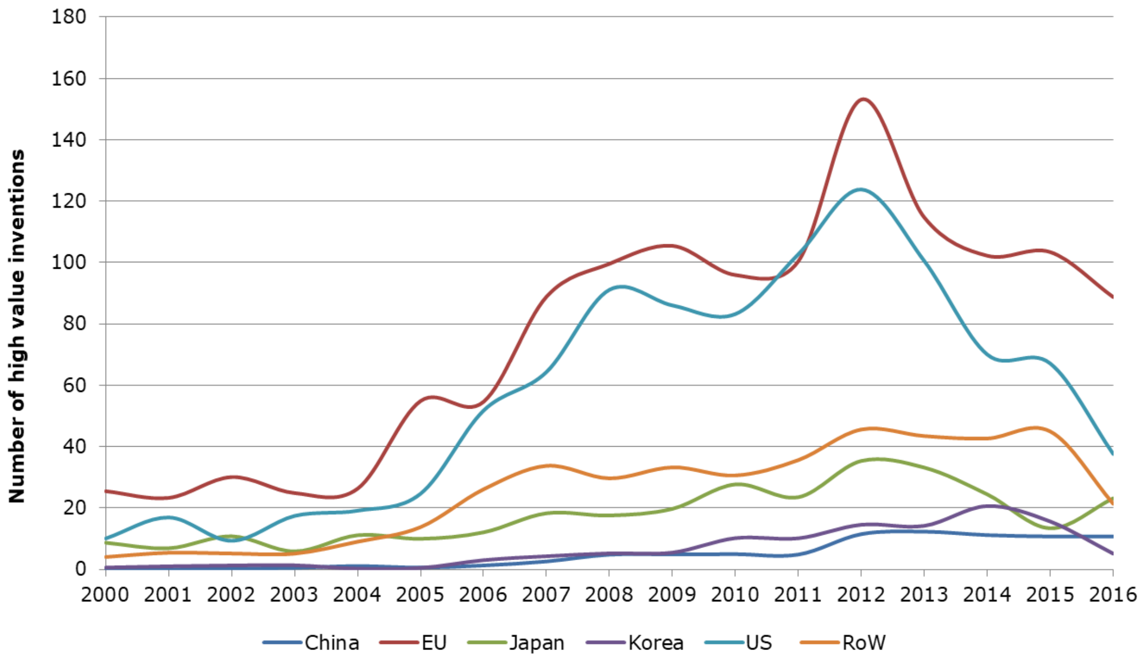


Figure 15. Trend of high value invention in 'Biofuels' and 'Fuel from waste' CPC classes (excluding torrefaction, grain bioethanol and methane production from landfill gas) by world player and year



3 R&D Overview

3.1 Overview of H2020 projects and SET-Plan flagship projects

This section collects background information on relevant EU H2020 funded projects[7] as well as SET-Plan flagship projects supporting advanced biofuels technologies.

Information on H2020 projects were collected from CORDIS, while the SET-Plan flagship projects were found in the document on 'Implementation Plan for the SET-Plan Action 8 on Bioenergy and Renewable Fuels for Sustainable Transport' prepared and made available by the Temporary Working Group as explained in section 1.1.

The data collection was set up for defined biochemical, thermochemical and oleochemical categories including the sub-technologies which are used for the production of advanced biofuels for transport purposes. The sub-technologies which were presented in section 2.1 include: fermentation, AD, BtL and SNG, fast pyrolysis, HTL, FAME and HVO/HEFA. Furthermore, projects indicated as 'bio-refineries', that do not refer to the considered technologies but include R&D on biomass availability or on the valorisation of side streams of advanced biofuels, were also included. We also report on funded projects, denoted as 'overarching/cross-cutting/support actions', which are dedicated to coordination and support actions with the general goal of boosting the development and deployment of advanced biofuels technology applications.

Figure 16 shows the number of H2020 projects (found in January 2020) that started between 2015 and 2020 and the corresponding total amount of EU public funding for each sub-technology. In Figure 17, the shares of public funding for each sub-technology over the total EU contribution are indicated.

Fermentation and biorefineries projects are the ones that received the greatest amount of EU funding in the advanced biofuel sector, with shares of 26% and 22% respectively. It should be also noted that three of the biorefineries projects include research on fermentation, therefore the amount attributed to fermentation can be actually considered even higher. Figure 16 indicates that amongst the selected sub-technologies, fermentation is not the one with the highest number of H2020 projects: this means that projects in fermentation are large projects in terms of total investment needed for their implementation. The highest number of projects was found in overarching followed by AD sub-technologies; however, the projects classified under these two sub-technologies seem to be generally small in terms of amount of public funding.

A lower amount of H2020 funding has been granted to thermochemical technologies: research projects were not found for SNG, but a growing number of projects was found in BtL, pyrolysis and HTL in comparison with the 2018 report. Amongst the thermochemical technologies, BtL received the biggest amount of support (more than 40 million EUR).

The oleochemical sector appears to be the one with the lowest amount of on-going research since both FAME and HVO have already reached a significant technological maturity; most of the research for these sub-technologies is on the use of alternative sustainable feedstocks such as algae.

Figure 18 shows biorefinery projects sub-divided on the basis of their main focus: production of fuels or other materials. Projects focussed on non-fuel, so-called 'multiple-products', typically aim to investigate the production of a range of different products such as bio-materials, bio-fertilisers, bio-polymers etc.

Figure 19 shows the total amount of EU funding per sub-technology by country. This helps identifying the leading countries that are mainly involved in the development of advanced biofuel projects. Germany is the country mostly involved in coordinating advanced biofuels H2020 projects, followed by Italy, France and Spain. Projects on fermentation and pyrolysis

[7] The projects and their information were collected from CORDIS between the 7th and 9th of January 2020. We restricted the analysis to the projects that mention biofuels as final product and projects with a minimum EU contribution of 250 thousand euro.

are mainly coordinated by Germany; research activities on fermentation are also led by Slovakia and France while Spain appears to be at the forefront of dedicated biorefineries projects.

Figure 16. Numbers of H2020 projects and total amount of EU funding (million EUR) identified for each advanced biofuel sub-technology

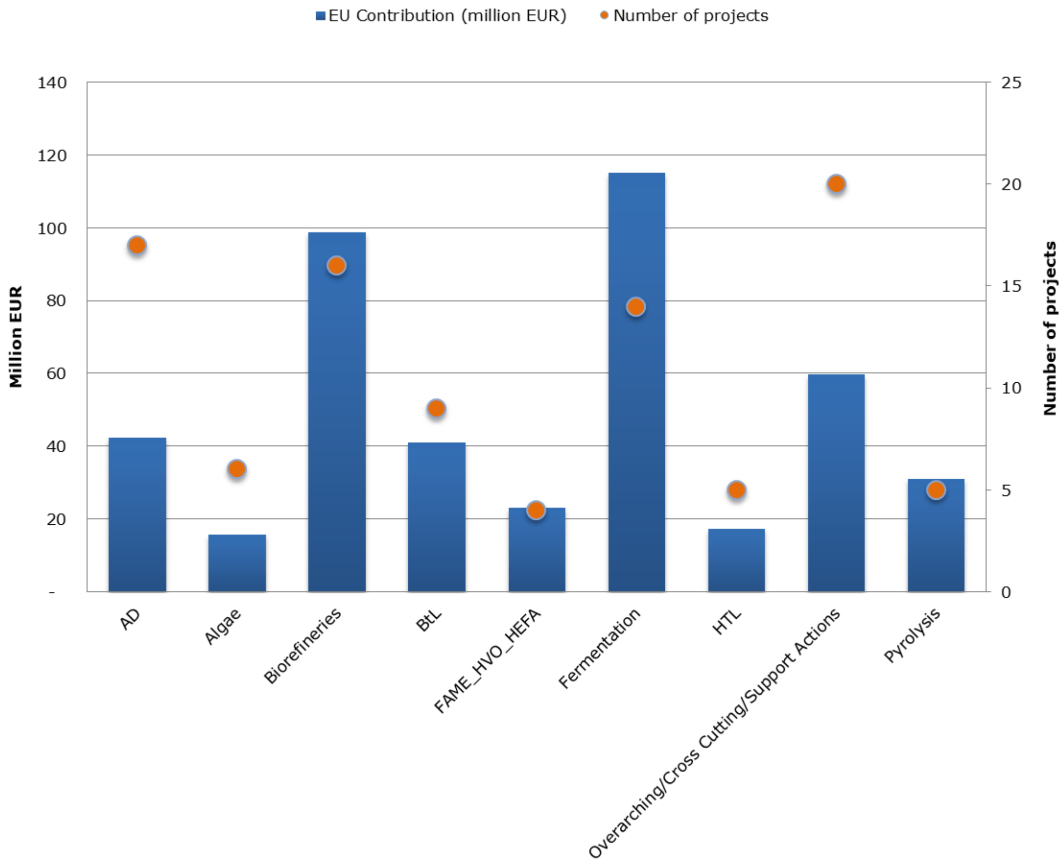


Figure 17. Shares of the EU funding for each advanced biofuel sub-technology based on the selected H2020 projects

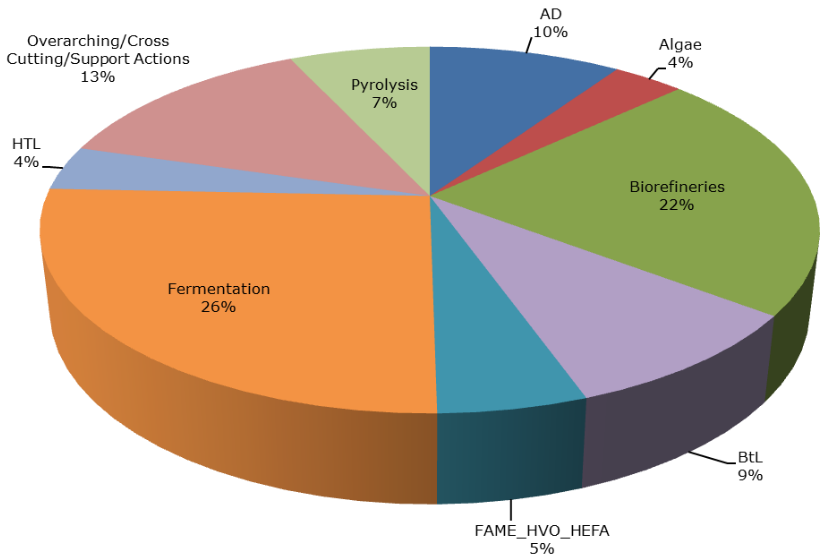


Figure 18. Shares of EU funding for biorefinery projects, sub-divided per technology

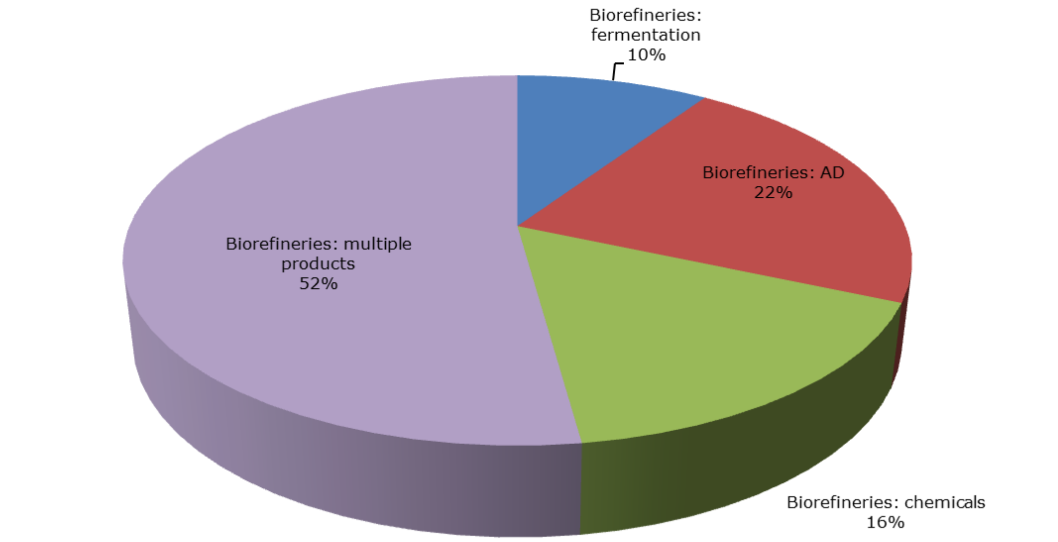
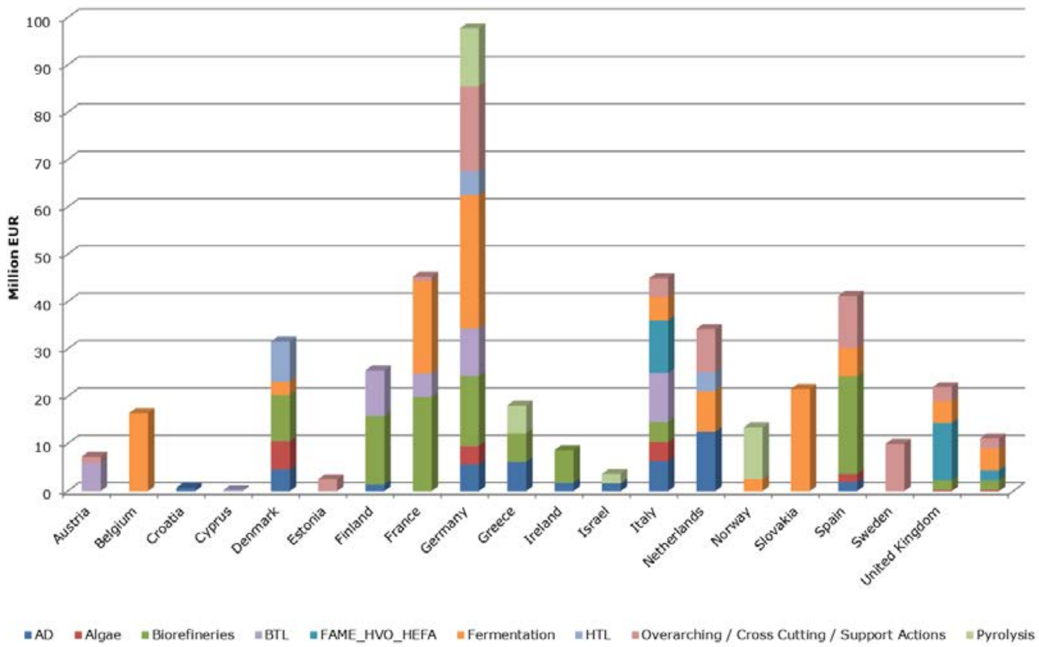


Figure 19. Total amount of H2020 EU funding (million EUR) for each advanced biofuel sub-technology by projects coordinator country



The complete list and general information on projects related to the above mentioned sub-technologies are provided in Table A 4 in Annex 2 for H2020 projects; data on start/end date, EU contribution, total cost, project's coordinator/country, and number of participants are reported in the table.

Table A 5 (Annex 2) reports the SET-Plan flagship projects/activities which are not already included in the list of H2020 projects. The SET-Plan 'flagship projects/activities', provided by the Temporary Working Group (TWG) on the 'Implementation Plan for the SET-Plan Action 8 on Bioenergy and Renewable Fuels for Sustainable Transport', are defined in the

Implementation Plan as “prominent ongoing R&I activities contributing to achieving the (SET Plan) targets and of interest to the public at large” (Implementation Plan, Action 8, 2018). Among the complete list of projects identified by the TWG we selected the ones which are related to the technologies under analysis in this report.

We selected, in total, 21 SET-Plan flagship projects/activities relevant for the technologies under analysis.

Table 7 reports some information on the initiatives classified by sub-technology including the country where it is implemented, the budget (that is not always available) and the timeline. Eight projects concern biochemical technologies, 12 projects are on thermochemical processes and one initiative is found in the oleochemical route. However, it’s worth noticing the difference in the budget involved in the initiatives; consistent investments (more than EUR 100 million) are foreseen for 2 BtL projects (one in France and one in Austria) and for the HVO installation in Italy. Two projects in fermentation also involve a relevant amount of investment (EUR 40 and 76 million in Austria and France respectively). Six projects are in pyrolysis including HTL and other technology. For the geographical distribution of the projects, Austria seem to be the country carrying out the largest number of initiatives (5) and covering different sub-technologies, followed by Italy with 4 projects and Finland that counts 3 projects on thermochemical routes.

A short description of the main objectives of H2020 and SET-Plan flagship projects in terms of TRL and key performance indicators (KPIs) will be provided in next section for each sub-technology.

Table 7. List of selected SET-Plan flagship projects by sub-technology (NA = Not Available)

Type	Name project/plant	Country	Timeline	Budget (EUR million)
Fermentation	Austrocel Hallein GmbH	Austria	2019 - 2020+	40
Fermentation	DELFT AB	Netherlands	2018 - 2022	NA
Fermentation	Eni Refinery	Italy	2018 - 2019	4
Fermentation	Futurol	France	NA	76.4 (including 29.9 national funding)
Fermentation	Oscyme	Austria	2017+	NA
AD	BioMethER	Italy	2013 - 2018 (delayed)	3.4
AD	VERBIO	Germany	2014 - 2019	Confidential (22 from NER300)
AD	PSI's catalytic fluidized bed technology	Switzerland	2016 - 2017	1
BtL	BioTFuel	France	2019 + (for commercial deployment)	178.1 (including 33.2 national funding)
BtL	BTL 2030	Finland	First phase 2016 - 2018	2.7 (first phase)
BtL	Güssing Gasifier	Austria	2018 - 2023	NA
BtL	Winddiesel	Austria	Not yet defined	150
SNG	AMBIGO	Netherlands	2018 - 2020	25
Pyrolysis	bioCRACK / bioBOOST	Austria	2007 - ongoing	12 (until now)
Pyrolysis	bioliq project	Germany	2005 - ongoing	NA
Pyrolysis	EMPYRO	Netherlands	NA	NA

Type	Name project/plant	Country	Timeline	Budget (EUR million)
Pyrolysis / HTL	Integration to refinery co-feed	Finland	Ongoing	5
Pyrolysis / HTL	Neste oil Porvoo refinery	Finland	Ongoing	NA
Pyrolysis / Other	RenFuel	Sweden	First phase 2015 - 2018	14
HTL	WASTE TO FUEL Gela Refinery	Italy	2017 - 2018	2.5
FAME_HVO_HEFA	Gela Green Refinery	Italy	2016 - 2018	240

3.1.1 Projects classified under 'biorefineries' and 'overarching/cross cutting/support actions': short summary

The projects assigned to the category 'bio-refineries', which are not analysed under the appropriate sub-technology in next sections, include R&D activities on:

- the valorisation of side-streams (such as lignin) to improve the cost-competitiveness and resource efficiency of lignocellulosic biorefineries (**LIGNINFIRST**, **LigniOx**) and other side streams (e.g. corn oil, thin stillage from bioethanol and rapeseed meal from biodiesel production) (**EXCornsEED**); the use of waste (such as the organic content of municipal solid waste or agricultural waste, co-products and by-products) as feedstock to produce different valuable marketable products for different bio-based markets including advanced biofuels (**URBIOFIN**, **AgroCycle**);
- the improvement and adaptation of industrial crop varieties (such as miscanthus and hemp) to diversify biomass feedstock for biorefineries (**GRACE**), and development of new approach to valorise the woody residue of plants (such as Salicornia) for biochemicals and bioenergy production (**AQUACOMBINE**);
- the use of marginal lands underutilized and contaminated lands for industrial crop production (**MAGIC**) and biomass for non-food purposes (**BIOPLAT-EU**);
- the development of mobile processes for the treatment of underexploited agro- and forest based biomass resources and processing into bio-products and intermediates (**MOBILE FLIP**).

Whereas, projects in the category 'overarching/cross-cutting/support actions' include R&D activities on:

- supporting the contributions of biofuel and bioenergy stakeholders to the Strategic Energy Technology (SET)-Plan (**ETIP Bioenergy-SABS**) and helping to achieve the key objectives of the European Industrial Bioenergy Initiative (EIBI) Implementation Plan bringing together national and transnational organisations (**BESTF3**, ERA-NET Co-fund project that follows two previous BESTF ERA-NET Plus initiatives);
- consolidating knowledge and establishing a centre of excellence in the field of 2nd and 3rd generation biofuels with the lead of European research infrastructures (**BRISK II** Networking Activities that builds upon its FP7 predecessor);
- providing education and research at on technologies that convert biomass into bioenergy (**ABWET; Phoenix; GasFermTEC**) and developing long term collaborations between universities (**BIOMASS-CCU**);
- developing and implementing strategies to build up knowledge on local availability of sustainable biomass feedstocks (including on underutilised lands and marginal lands) and know-how on issues from logistics to storage and conversion pathways to renewable energy at EU and local level increasing the demand and supply of bioenergy products and involving local biomass suppliers, energy producers and

financial sector players (**BioReg, BioRES, FORBIO, greenGain, SecureChain, SEEMLA, Up_running**; **MUSIC)**.

- looking at the final use in vehicles (**COLHD)** and the compatibility of biofuels in the current fuel system in aviation (**JETSCREEN**) and enabling the commercialization of advanced and liquid renewable alternative fuels (**ADVANCEFUEL**).
- facilitating bioenergy retrofitting in five industries (first-generation biofuels, pulp and paper, fossil refineries, fossil firing power and combined heat and power plants (**BIOFIT**).

4 Impact assessment

This section provides a short description of the main objectives and expected results of H2020 (on the basis of the information available on CORDIS) and SET-Plan flagship projects. The overall goal is to provide an insight on the contribution of the selected projects to the development of a certain technology. The focus will be on projects closed by February 2020; however, for sub-technologies for which no project was closed by the time of the update of this report, the status of on-going projects will be reported if available.

An overview of national (in addition to the SET-Plan flagship projects) and international initiatives or projects is also provided for each sub-technology.

4.1 Biochemical technologies

4.1.1 Fermentation: focus of H2020 EU and Set-Plan flagship projects

A number of projects attempt to prove the viability of integrated or whole-process cellulosic fermentation systems. Seventeen projects are projects on fermentation, six of which are closed at the time of writing the report.

BABET-REAL5 (2016-2020) is a recently closed project which aimed to develop an alternative solution for the production of second generation ethanol based on smaller industrial scales (and hence less feedstock-intensive) compared to first generation ethanol plants. The major achievement was the development of a one-stage-reactor for the pretreatment of biomass and the saccharification/fermentation process.

WASTE2FUELS (2016-2018) intended to produce, and improve the production of butanol from agro-food waste streams via the ABE (acetone-butanol-ethanol) process, and by catalytic conversion of ethanol. Novel pre-treatment methods converting agro-food waste were developed, the production process was improved achieving higher conversion efficiencies and post process waste streams and by-products were valorised. The **ButaNexT** project (2015-2018) was also focused on fermentation of butanol by optimising the ABE process with the aim of improving costs and energy efficiencies. Improved processing and product recovery steps were reported. The project was able to optimise all the individual stages of biobutanol production. In particular, the project was able to: develop an innovative two-stage biomass pre-treatment and tailor made enzyme cocktails to convert sugars at higher yield with lower energy use and costs; obtain high productivity fermentation process combining novel microbial strains with in situ product recovery; integrate the technologies and upscale the process to pilot scale.

US4GREENCHEM (2015-2019) also aimed to improve the overall production chain, defining their pathway as a bio-refinery which requires optimisation as every step, not just for the production of ethanol. However, at the time of writing the report, there is no available information on the project's results in CORDIS.

Another project focused more on improving individual facets of the production chain; the **APEX** project (2015-2017) reported reductions in cost and improved enzyme performance for the liberation of cellulose from lignocellulose to be used in industrial processes (pulp and paper mills and biorefinery pilots).

On-going projects with very significant EU funding include:

The **LIGNOFLAG** project (2017-2022; EU contribution: EUR 24.7 million) which includes Clariant amongst its partners, aims to build a flagship fully commercial scale cellulosic ethanol plant, using Clariant's own technology (sunliquid®). In 2018, Clariant officially started the construction of the first large-scale commercial plant for the production of cellulosic ethanol (with an annual capacity of 50 000 tonnes) from agricultural residues in Romania. This project could be a critical project towards final development of large-scale and robust cellulosic ethanol production. The aim of the project is to optimize the efficiency and increase the production capacity of the plant to up to 60 000 tonnes of ethanol per year, as well as to ensure a highly sustainable production process that uses co-products for renewable energy production and soil fertilization.

BIOSKOH (2016-2022; EU contribution: EUR 13.9 million) is a flagship research project aiming to have an overall industrial scale production of 55 000 tons per annum of cellulosic ethanol). BIOSKOH aims to transform a brownfield industrial site in eastern Slovakia into a cellulosic ethanol production facility. If successful, it would be highly significant. This project was previously coordinated by BIOCHEMTEX (Italy) while, at the time of writing this report, it appears to be coordinated by ENERGOCHEMICA TRADING AS (Slovakia).

The REWOFUEL (2018-2022; EU contribution: EUR 21.6 million) project aims to demonstrate the entire value chain from residual wood to 3 high performance drop-in biofuels derived from bio-Isobutene (bio-IBN). These biofuels are full-bio-ETBE, bio-isooctane and bio-isododecane rich biofuels. REWOFUEL includes the development & up-scaling of this process and the valorization of coproducts.

Concerning microbial fermentation of gases, **Torero** (2017-2020; EU contribution: EUR 11.5 million and also a SET-Plan flagship project), is working to show the viability of this pathway. The project will demonstrate a technology concept for producing bioethanol in a fully integrated large-scale, industrially functional steel mill. Wood waste is converted to biocoal by torrefaction and biocoal is used to replace fossil powdered coal in the steel mill blast furnace. The overall aim is to prove the OPEX for this form of production can be 1/3rd lower than regular cellulosic ethanol production from sugars.

Considering other SET-Plan flagship projects at a national level, the **AustroCel Hallein** biorefinery in Austria planned for 2019/2020, aims to produce up to 12 000 tonnes per year of ethanol using cellulose extracted from sulphite spent liquor (SSL) from a spruce wood pulping plant. Normally the SSL is used to make steam and electricity for the pulping plant, the project aims to use the by-products from their process to do the same, once the fermentable fraction has been made into ethanol first. **Oscyme**, a lower TRL project focussed specifically on reducing costs and improving the efficiency of the critical hydrolysis step, began in 2017 and is also based in Austria. **DELFT AB** in the Netherlands, a collaboration which includes Delft University and for biofuels, DSM, have a pilot facility aimed at helping scale-up of processes for making cellulosic ethanol. The French-funded **Futurol** project, in conjunction with technology providers Axens, is an EUR 76 million initiative aiming to validate at industrial scale, a complete working cellulosic ethanol facility, including full conversion of both C5 and C6 sugars. For microbial fermentation, **ENI** in Italy have a EUR 4 million project on-going to investigate the production of oils suitable for subsequent fermentation.

The integration of biochemical and thermochemical methods was investigated by the **Ambition** project (2016-2019) with the aim of increasing the feedstock base for advanced biofuels production and feedstock utilization through the integration of energy systems. The project included work on biomass pretreatment processes and fermentation of simulated syngas from lignin gasification. According to the project partners, syngas fermentation with crude syngas from different types of biomass and different gasification methods is currently at TRL 1-2 and the aim is to move to TRL 3-4 in order to access the varieties of syngas qualities.

4.1.2 Fermentation: focus of international projects

The **U.S. Department of Agriculture** has an Advanced Biofuel Payment Program (ABPP) that aims to support and ensure an expanding production of advanced biofuels. The USDA's Rural Business Cooperative Service published a notice in December 2019 seeking applications from biofuel producers. The notice was published concurrently with the issuance of the final rule for the Bioenergy Program for Advanced biofuels. The USDA announces the availability of up to USD 7 million for each for fiscal years 2019 and 2020 to make payments to eligible advanced biofuel producers for the production of eligible advanced biofuels (Voegele, 2019).

The Department of Energy (DoE) is supporting R&D projects through the Biomass Research and Development Initiative (BRDI). In 2018, DoE announced up to USD 3 million in funding for advanced biofuels, bioenergy, and biobased products and two selected projects received between USD 1 to 2 million to develop biofuels from cellulosic ethanol and ligno-cellulosic biomass, respectively. Other funding is available under the BioEnergy Engineering for Products Synthesis program (total of up to USD 28 million in 2018), supporting projects that are aiming to create efficient conversion processes for biomass and waste derived fuels. Process Development for Advanced Biofuels and Biopower is another program that supports 10 projects with USD 22 million (Padella et al., 2019). **Canada** continues with its CAD 500 million 'NextGen Biofuels Fund' to help cellulosic ethanol and other projects get to market by helping them with their capital expenditures, managed by Sustainable Development Technology Canada (SDTC). The fund aims to: (i) facilitate the establishment of first-of-kind, large scale demonstration facilities for the production of next-generation biofuels and co-products in Canada; (ii) improve the sustainable development impacts arising from the production and use of biofuels in Canada, and (iii) encourage retention and growth of technology expertise and innovation capacity for the production of next-generation biofuels in Canada. Applicants must demonstrate their technology works at the pre-commercial pilot scale. In **Brazil**, BNDES and Brazil's research-financing agency Finep established the Joint Support Plan for Industrial Technological Innovation in Sugarcane-based Ethanol and Chemistry Sectors (PAISS). It is aimed at increasing productivity in the sector by developing new industrial technologies, including advanced cellulosic ethanol. BNDES will provide funding of BRL 1.9 billion (EUR 624 million) to companies for growing operations at ethanol and sugar plants. BNDES and Finep have so far chosen 35 projects from 29 companies for loans under the PAISS programme. The budget has increased by 30% from the BRL 1.48 billion previously scheduled. The PAISS programme's aim is to increase income at plants by generating more value from cane, increasing margins at a time when production costs surge and ethanol prices drop. **Chinese** policy dictates biofuel development cannot compete with crops intended for human or animal consumption, although corn grades unfit for human consumption are allowed. China has improved the ability of their microbes to withstand higher than usual levels of alcohol, having reached an improvement up to almost 16% alcohol, verified at industrial level. This work allowed one of their facilities to reduce its energy costs by USD 2 million per year. In addition, second generation ethanol production is focussed on using corn stover but also as an add-on to first generation ethanol facilities. China has an E10 mandate in place, and expects an E20 mandate in future; given this and the restrictions on the use of food crops, they are putting increasing focus on proliferating second generation ethanol. **Japan** is investigating the development of bioenergy, biochemical and biomaterials through NEDO (New Energy and Industrial Technology Development Organisation) and AIST (National Institute for Advanced Industrial Science and Technology). This work includes the strategic development of next-gen bioenergy utilisation technology.

4.1.3 Anaerobic Digestion: focus of EU and SET-Plan flagship projects

A short summary of the main objectives (and funding scheme) of the most relevant projects on AD is reported below.

ADD-ON (SME-2) project focuses on the scale-up of the pilot plant to remove nitrogen from feedstock and valorise it as fertilizer. The project claims to be able to remove over 60% of nitrogen from several complex feedstocks, such as organic waste e.g. chicken manure; thus, enabling the use of millions of tons of unexploited organic waste in Europe.

BIN2GRID (CSA): the overall objective of Bin2Grid concept is to promote segregated collection of food waste as energy source, conversion to biogas, and its upgrading to biomethane and utilization in associated network of filling stations. To that end, accent was given to defining strategies for establishing efficient network of food and beverage waste collection methods and practices.

In the **BIOFERLUDAN** (SME-1) project, the LRE company aims to scale-up its experience on cost-effective and reliable treatment of the digestate, developing an on-site recovery process to treat it, obtaining high quality liquid, humic fertilizers. Based on previous R&D works done by LRE, a biogas plant that uses the BIOFERLUDAN process will produce a minimum of 60 liters of fertilizer per ton of digestate.

BIOFRIGAS (SME-1) aims to scale down technologies for producing Liquefide BioGas (LBG). Biofrigas Sweden AB has developed and piloted an effective, decentralised, small-scale and affordable, containerized energy plant that converts manure into 97% pure liquefied biogas (LBG).

BIOGASACTION (CSA) aims to promote the development of the European biogas removing non-technical barriers to widespread production of biogas/biomethane from manure and other waste. The project aims to boost biogas development in target regions in conjunction with replication efforts and promotion at EU scale.

BIOGASTIGER (SME-2) aims to demonstrate performances of a modular compact biogas plant in a transportable container construction. All components are standardized and industrially premanufactured in series.

The aim of **BIOSURF** (CSA) is to increase the production and use of biomethane for grid injection and as transport fuel, by removing non-technical barriers and by paving the way towards a European biomethane market. The main ideas of BIOSURF are to develop a value chain analysis, to compare and promote biomethane registering, labelling, certification and trade practices in Europe and to address traceability, environmental criteria and quality standards, in order to reduce GHG emissions and indirect land use change (ILUC).

The objective of **DEMETER** (BBI-IA-DEMO) is to increase the yield of biogas production from organic waste by at least 20%, improve the product recovery process by 40%, and reduce overall product cost by at least 15% while increasing the productivity of the process by applying a new enzyme product.

DEPURGAN (SME-2) aims to bring to the market an efficient pig manure treatment process, with an initial investment significantly lower compared to other solutions and operation costs being also very competitive. It bases its innovative character in the use of an optimized electrocoagulation reactor, which allows nitrogen abatement, while producing as residues a solid fraction that poses great calorific potential as biomass, and a NPK liquid effluent ready to be used as fertilizer.

HOMEBIOGAS (SME-2) aims to convert organic waste (100 kg per day) into free clean energy (120 kWh per day), generating important cost savings (over EUR 5 000 per year) and improving their environmental footprint and corporate image. HOMEBIOGAS has been demonstrated at TRL6 through the successful development and commercialisation of the pilot system and the development and trial of two different large (200-250 kg per day) business-to-business pilots.

ISAAC (CSA): the main project objective consists on the construction of communicative model oriented to spread balanced information, based on environmental and economic benefits, between all the actors potentially involved in biogas/biomethane implementation. At the same time, actions will be focused on reducing the fragmentation between farmers, foresters and other stakeholders in order to reach the minimal facility dimension needed, increasing biogas and biomethane penetration and reducing cost management. A participatory process model will be developed as the main project's approach is to reduce social conflict and to include all actors in important common decision-making process; starting from the experience, a normative proposal on the participatory process will be recommended.

ISABEL (CSA) aims to promote energy transition by employing modern marketing research to understand the needs and cultural diversities of the communities, focusing on repositioning biogas from an economic biofuel carrier to a social good, to come up with new community concepts and to build a stronger and wider community engagement in support of biogas. Project zooms on specific areas with diverse interest, thus supporting communities on the ground to realize community biogas plans in coordination with all the stakeholders, slashing transaction overheads.

Lt-AD (SME-2) proposes a low-temperature anaerobic digestion (Lt-AD) process, able to provide a novel solution to Food and Drinks industrial sectors which produce large volumes of waste water. This Phase 2 project will allow the company NVP Energy to install and commission a demonstrator plant and gain 8-12 months operational data.

MUBIC (SME-2): the AST technology creates a resource cycle between biogas production and mushroom production, reducing costs of mushroom production by up to 50% and utilizing also the fibrous fraction in biogas plants. The innovation is a technology where the fibrous fraction from biogas is used for growing mushrooms, and then returned to the biogas plant, offering improved economy as well as significant environmental benefits to both the mushroom and biogas industry. A full scale demonstration plant is in operation (Panbo, Netherlands) and a patent has been filed.

Record BIOMAP (CSA): the objective of the project is to establish the most promising innovative process and technology solutions along the biomethane supply chain, from raw material/residues, substrate pretreatment, digestion, gas conditioning/digestate and further utilisation of digestate/fertilizer in a cost effective manner and to support the market uptake. To bridge the gap between research and market, a biomethane platform is established to support the dissemination and exploitation of the knowledge ascertained in the project to the industry sector, the end users and other important stakeholders, and therefore to foster the use of research outcomes.

SYSTEMIC (IA) aims to reach a break-through to re-enter recovered nutrients from organic waste into the production cycle. It aims to offer solutions for pressing environmental issues and to reduce the import of Phosphorus as finite irreplaceable resource in mines.

DECISIVE (IA) proposes to change the present urban metabolism for organic matter (foods, plants, etc.), energy and biowaste to a more circular economy and to assess the impacts of these changes on the whole waste management cycle. Thus, the challenge will be to shift from an urban "grey box", implying mainly goods importation and extra-urban waste management, to a cooperative organization of intra- and peri-urban networks enabling circular local and decentralised valorisation of biowaste, through energy and bioproducts production.

The **INCOVER** (IA) concept has been designed to move wastewater treatment from being primarily a sanitation technology towards a bio-product recovery industry and a recycled water supplier. A wastewater specific Decision Support System methodology has been tailored to the INCOVER technologies and provide data and selection criteria for a holistic wastewater management approach. Three added-value plants treating wastewater from three case-studies (municipalities, farms and food and beverage industries) have been implemented, assessed and optimised concurrently. INCOVER plants are implemented at demonstration scale in order to achieve Technology Readiness Level (TRL) of 7-8.

NoAW (RIA): driven by a "near zero-waste" society requirement, the goal of the project is to generate innovative efficient approaches to convert growing agricultural waste issues into eco-efficient bio-based products opportunities with direct benefits for the environment, the economy and the EU consumer. To achieve this goal, the NoAW concept relies on developing holistic life cycle thinking able to support environmentally responsible R&D innovations on agro-waste conversion at different TRLs, in light of regional and seasonal specificities, not forgetting risks emerging from circular management of agro-wastes (e.g. contaminants accumulation). By involving all agriculture chain stakeholders in a territorial perspective, the project will: (1) develop innovative eco-design and hybrid assessment tools of circular agro-waste management strategies; (2) develop breakthrough knowledge on agro-waste molecular complexity and heterogeneity in order to upgrade the most widespread mature conversion technology (anaerobic digestion); and (3) get insights of the complexity of potentially new, cross-sectors, business clusters in order to fast track NoAW strategies toward the field and develop new business concepts and stakeholders platform for cross-chain valorisation of agro-waste on a territorial and seasonal basis.

It is also worth mentioning the SET-Plan flagship initiative **COSYMA** (Container-based System for Methanation) of the Swiss Paul Scherrer Institute (PSI) in collaboration with Energie 360°. This is a methanation reactor (see section 2.2.2 and 4.2.3 for further details), which is using biogas for supply. The heart of the technology is a fluidised bed reactor; in it, the raw biogas and the added hydrogen, bubble through and mix with particles of nickel catalyst. A long-duration test has been successfully conducted in spring 2017. The actual limits for a large scale development are costs; therefore, assessing the economic viability of direct methanation within the context of biogas processing is part of the next steps of the project.

The **VERBIO** project, supported by the NER300 founding scheme and recognised by the SET-PLAN as a flagship initiative, aims to progress innovative AD technology to produce biomethane from 100% straw. The plant is located in Schwedt/Oderand has a capacity of 16.5 MW, using 40 000 tonnes/yr of input straw. The project is on-going.

4.1.4 Anaerobic Digestion: focus of international projects

Amongst the world areas where biogas is a relevant technology, Asia and US are the most important. South America, Brazil and Argentina have also interesting potentials. Despite of that, it is worth noticing that European installed capacity and potential for biomethane currently results abundantly higher than any other country.

The USA biogas potential can be estimated, according to the American Biogas Council (ABC, 2018) in 977 MW (about 1.4 billion cubic meters), based on over 2 200 digesters. Among these installations, 1 269 are at wastewater recovery facilities, 636 capture landfill gas, 259 treat dairy or swine manure, 39 treat only food waste, and the rest treat industrial waste (EESI, 2018; AgSTAR, 2017). Ongoing efforts are being made through a number of programmes at the US Department of Agriculture (USDA), US Department of Energy (DOE) and Environmental Protection Agency (EPA). Priority areas of current US programs comprise the efficient biogas production, recovery and pathways utilization, as well as market development of non-energy products from biogas systems. As a part of the Clean Cities strategic plan, DOE jointly with Argonne National Laboratory (ANL) is developing a database of existing and planned projects producing renewable natural gas (RNG) for vehicle fuel or pipeline injection. The goal is to strengthen programs that support the use of RNG from biogas to compressed or liquid vehicle fuels directly. In addition, the aim is to promote RNG as a feedstock for generating renewable transportation fuels, such as gasoline, diesel, jet fuel, hydrogen and DME. Within the AgSTAR National Mapping Tool, EPA aims to map the potential sources of food and other organic waste materials available in a given area. The overarching goal is to engage stakeholders, address key barriers and support developers of projects on biogas systems (USDA-EPA-DOE, 2014). Within the Renewable Fuel Standard (RFS), the US EPA classified many sources of biogas as cellulosic feedstock for transportation fuels. According to this classification, cellulosic biofuels are among the most promising advanced biofuels (USDA-EPA-DOE, 2014). Production of biogas from lignocellulosic feedstock, as well as algal biomass and waste is one of the key research areas of DOE's Bioenergy Technologies Office (BETO) programs. The technologies are at early stages of development based on pilot and/or demonstration projects. The increase in value of credits ('renewable identification numbers' or 'RINs') from the advanced cellulosic section of the Renewable fuel Standard coupled with low natural gas prices for generating cheap fossil electricity has made biogas projects that produce vehicle fuel much more economically attractive to develop than biogas projects that produce electricity in most locations.

Since 2000, the Chinese government has been promoting rural biogas plants, as suitable solution to two major problems: the rural energy shortage and widespread environmental pollution. China government is providing incentives and financial supports for developing applications for biogas technology mainly from waste treatment (Deng et al., 2017). Over 40 million household scale reactors and 30 000 large-scale digesters were built in China in 2010 (Song et al., 2014); the total biogas production can be estimated 1.58 billion cubic meters (BCM) in 2012 (Wang et al., 2012). The possibility to use lignocellulosic feedstock is a clear target in new projects, whereas biomethane upgrade seems to be less relevant.

Current biogas production in India is estimated in 2.07 BCM/y (MNRE, 2016). This amount is low compared to the Indian potential, which is estimated to be in the range of 29–48 BCM, and support schemes such as the National Biogas and Manure Management Program (NBMMP), off–grid biogas power generation program, waste to energy program have been implemented by the government for biogas development in India (MNRE, 2016). Regardless of these efforts, the diffusion of biogas technologies is still low and innovation is not the focus of the initiatives (Mittal, 2018).

In Brazil, the number of plants is really low and few initiatives are on-going. The sector potential is 114.7 MW of power (dos Santos, 2018).

As for the previous report, in Australia, R&D programmes are focusing on the conversion of biomass residues, e.g. sugarcane waste and bagasse, to biogas which can be upgraded to biomethane for use in farming and transportation. R&D is on-going for the conversion of solids from biogas production, by HTL technology. Key research areas include the improvement of the efficiency and economics of biomass conversion for the production of energy and chemical products (ARENA, 2016).

4.2 Thermochemical technologies

4.2.1 Gasification with Fisher Tropsch synthesis for BtL production: focus of EU and SET-Plan flagship projects

Eight H2020 projects and four SET-Plan Flagship Projects include R&D work on BtL technology with focuses on the development of innovative concepts or integrated processes able to overcome the issues related to the gasification, FT-synthesis and fuel upgrading steps and on the expansion of biomass feedstocks that can be used in the process.

The aim of the **COMSYN** project (2017-2021) is to develop a new BTL production concept based on small-to-medium scale (10-50 ktonnes/y FT products) conversion units that will be located close to various types of biomass sources (e.g. woody residues, agricultural residues, waste-derived materials) and will be integrated with local heat and power production. The FT products will be then refined to liquid transport fuels at existing oil refineries. The consortium claims to be able to reduce biofuel production cost up to 35% compared to alternative routes (< 0.80 EUR/l production cost for diesel). The gasification-FT process has been successfully validated by VTT (the Technical Research Centre of Finland) in September 2019. Two products, the FT- wax and FT-oil streams, were collected and will be further refined to high quality transport fuels by UniCRE, the Unipetrol Centre for Research and Education, assisted by VTT. This project has also been denoted as a SET-Plan flagship project because of its contribution to achieving the SET-Plan targets in particular on reducing biofuel production costs.

The focus of the **FLEDGED** project (2016-2020) is on the production of bio-based dimethyl Ether (DME) from biomass. The consortium aims to develop and validate a novel biomass to DME process in an industrially relevant environment (at TRL 5) combining two key sub-processes (flexible sorption enhanced gasification (SEG) and sorption enhanced DME synthesis (SEDMES) processes). The combination of the two sub-processes will provide more flexibility, and a more efficient process compared to other routes for the DME synthesis with expected lower production costs.

The **Heat-to-Fuel** project (2017-2021) intends to develop an innovative integrated system for the production of biofuels. Conversion processes will be integrated for the biomass conversion into one single innovative concept: dry organic waste will be converted by gasification and Fischer-Tropsch (FT) synthesis; while wet organic waste (e.g. lignin-rich residues) will be converted by hydrothermal liquefaction and hydro-treating. Synergies will be implemented across the two processes to promote heat integration at system level, including production of hydrogen from carbon-laden water reforming into hydrogen (acqueous phase reforming between the liquefaction and FT units). The integrated approach will enable to maximize the total process efficiency and ultimately to reduce production costs. This project is also a SET-Plan flagship project for its contribution to achieving the SET-Plan targets.

New projects recently started are briefly described below.

CLARA (2018-2022) aims at further developing Chemical Looping Gasification (CLG) which has only been investigated at lab-scale (up to 25 kWth feedstock input) using a broad range of pilot plants up to 1 MWth. **CONVERGE** (2018-2022) will develop from TRL 3 to TRL 5 the integration of five technologies (including catalytic cracking of tars from a gasifier integrated with recovery of refinery products; sorption-enhanced reforming for H2 and CO2 separation, integrated with highly efficient electrochemical compression of green H2 with by-product fuel; enhanced methanol membrane synthesis to ensure green biodiesel production) that will increase the biodiesel production from wood-based biomass. The scope of **FLEXCHX** (2018-2021) is to develop a hybrid process that integrates electrolysis to biomass gasification and synthesis and to validate the key enabling technologies at TRL 5. **Pulp and Fuel**'s (2018-2022) overall objective is to increase the yield of biofuels developing a simple and robust fuel synthesis process integrated on a pulp mill taking advantage of the synergy between super critical water gasification (wet gasification) and fixed bed gasification (dry gasification). **REDIFUEL** (2018-2021) aims to develop process designs for a small and an intermediate size, fully integrated production plant starting from various biomass (bio)syngas to a drop in renewable fuel.

The SET-Plan flagship project '**Güssing Gasifier**' (2018-2023) carried out by Bioenergy2020+ aims to install a new research, pre-industrial gasifier for (co-)firing woody biomass, agricultural residues, sewage sludge and plastic waste. The gasifier will be able to produce kerosene (via FT synthesis) and phosphorus recycling will be also investigated. The used technology is high-temperature gasification in dual-fluidised bed to synthesis gas (CO, H_2) and the downstream processing will include different routes to gases, liquids and chemicals (e.g. methanation, Fischer-Tropsch synthesis).

Winddiesel is a SET-Plan flagship project coordinated by the Austrian research Institute Güssing Energy Technologies GmbH (GET) (Winddiesel website). The project timeline has not been defined yet. The aim of the project is to integrate a biomass-to-liquid (BtL) plant with hydrogen produced by electrolysis using renewable (wind) electricity. This will increase the final fuel production by 75% according to the technology providers. The basic process consists of a DFB (Dual Fluidised Bed) gasification plant and a downstream Fischer-Tropsch part; the major innovation of the process is considered to be the change in the syngas ratio to allow additional hydrogen to be fed. For this purpose, the gasification part of the DFB plant is fluidized with CO_2 instead of steam, and large amounts of hydrogen can be fed.

The **BTL 2030** (2016-2018 first phase) on 'Production of transport fuels from biomass by gasification-based concepts integrated to energy consuming industries and district heat power plants-pilot tests and feasibility studies' carried out by VTT in Finland (in collaboration with 11 industrial partners) aims to develop a medium-scale BtL concept which can be integrated to different kind of energy intensive industries and district heating power plants using forest residues. The first phase of the project includes pilot tests based on VTTs dual fluidised-bed gasification (DFB) technology as well as system and feasibility studies while the first production plant is planned for 2021 (VTT website).

The **BioTFuel** project by Total in France is also defined as a SET-Plan flagship project. The project was launched in 2010 by six partners (Axens, IFP Energies Nouvelles, the French Alternative Energies and Atomic Energy Commission (CEA), Sofiprotéol, ThyssenKrupp Uhde and Total) with the aim to integrate all the stages of the BtL process chain and bring them to market in 2020. The project includes the construction and operation of two demo plants in France to produce biodiesel and biokerosene (bio-jet fuel) based on biomass gasification. The project was partly financed by public funding (EUR 33 million).

4.2.2 Gasification with Fisher Tropsch synthesis for BtL production: focus of national and international projects

In EU, national initiatives on gasification and BtL were found in Finland and UK in addition to the SET-Plan flagship projects reported above. One project led by VTT (Technical Research Centre of Finland) was funded by the Finnish Funding Agency for Innovation (Tekes) in **Finland**: BTL2030 project[8] (2016 – 2018). It received EUR 1.5 million from Tekes and aims to develop a new gasification process for heat integrated production of transport fuels.

Outside EU, relevant international pilot/demonstration projects in the **US** were partly supported by DoE funding. These include: Frontline Bioenergy; Des Plaines, Sundrop Biofuels (project did not start) and Red Rock Biofuels LLC also described in section 2.3.1.

A number of research projects on gasification are supported by the Bioenergy Technologies Office (BETO) of the Department of Energy (DoE). In the framework of the seventh biennial external review of the BETO's R&D portfolio (BETO, 2017), external experts reviewed a total of 33 projects (carried out between 2015 and 2017) on thermochemical conversion technologies that include gasification, liquefaction and fast pyrolysis as main research areas. The review addressed a total DOE investment of approximately USD 145 million, which represents approximately 20% of BETO's portfolio. The review is designed to assess the projects and collect external stakeholder recommendations on the overall scope and strategic direction of the research.

According to the reviewers, enough technological and operational progress was generally achieved in the 2015–2017 period and key milestones were reached for some technologies, suggesting additional focus on some pathways and reduced focus on others. The liquefaction and gasification projects in particular were ranked highly and considered as leading the current state of the art. According to the reviewers, significant progresses were made in these technology areas which have real commercial potential in the near to medium term. A continued focus on improving process efficiencies and generating high-value products have been suggested in order to maintain the cutting-edge status of these technologies and reach significant economies of scale.

The reviewers also suggested considering a shift in BETO's project portfolio to include more technologies designed to function at smaller scales in order to have a much higher probability of being commercialized. Moreover, projects making a significant effort to utilize existing commercial facilities or commercially relevant reactors to prove a conversion step were identified as high priority as they will generate data critically important for accelerating the commercialization process. The valorisation of existing biorefining waste and product streams should be also the focus of future projects.

4.2.3 Gasification with methanation for SNG production: focus of EU and non-EU projects

Unfortunately, all the major European projects involving SNG from biomass gasification are currently on-hold or cancelled, with the only exception of the AMBIGO project (see section 2.3.2. Current activities on biomass gasification seem to focus on BtL production via FT process, instead of producing SNG. Despite of this picture, the SNG from methanation reaction is still an interesting technology but today projects are considering it a step of the power-to-gas pathway (that will be discussed in the alternative advanced biofuel technology report).

[8] 'Production of transport fuels from biomass by gasification-based concepts integrated to energy consuming industries and district heat power plants– pilot tests and feasibility studies'.

In US, bio-SNG production is considered as an option for many of the projects already described in section 2.3.2; nevertheless, no significant initiative seems to be on-going and, this is in general true for the other non-EU major countries.

4.2.4 Fast Pyrolysis and HTL: focus of EU and SET-Plan flagship projects

Ten projects include work on pyrolysis and/or hydrothermal liquefaction with the final aim to produce drop-in fuels.

The **BioMates** project (2016-2020) aims to develop and validate a TRL 5 biomass conversion technology (using straw and miscanthus) for the production of high-quality renewable intermediates (called BioMates), to be used in any conventional refinery and converted to transportation fuels. The original proposed technology combined two thermochemical processes for the production of the BioMates: ablative fast pyrolysis (AFP) and mild catalytic hydrotreatment (mild-HDT).

The **4REFINERY** project (2017-2021) aims to develop and demonstrate up to pilot the production of advanced biofuels from two primary conversion routes (catalytic fast pyrolysis and hydrothermal liquefaction) integrated with upgraded (hydro)refining processes. The bio-liquids produced by fast pyrolysis and hydrothermal liquefaction will be co-processed in the most relevant refinery upgrading technologies: co-Fluid Catalytic Cracking co-hydrodeoxygenation and co-hydrotreating. The project focuses on process optimization, overall chain improvement, and integration in existing refinery processes. This project is also a SET-Plan flagship project for its contribution to achieving the SET-Plan targets. According to first published periodic report, 100 litres of stabilized pyrolysis oil (SPO) and 60 kg of hydrothermal liquefaction liquids (HTL) were produced. The two bio-oils are being investigated in alternative co-refining steps to establish the basis for selecting the optimal co-refining routes, considering the feedstock and end use application.

A more recent H2020 project is **WASTE2ROAD** (2018-2022). This project also looks at both fast pyrolysis and hydrothermal liquefaction processes. The full value chain will be covered: from waste management and pre-treatment of waste streams from households, to transformation to bio-liquids through fast pyrolysis and hydrothermal liquefaction and production of advanced biofuels via intermediate refining processes combined with existing downstream refinery co-processing technologies including the assessment of the end-use compatibility of the obtained biofuels for road transport applications.

The **bioCRACK** pilot plant[9], in the OMV refinery in Vienna (until 2015), and the **bioBOOST** laboratory testing at the Graz University of Technology (ongoing) are two related projects defined as SET-Plan flagship projects. The bioCRACK process (mentioned also in section 2.3.3) is a patented technology developed since 2010 for the production of second generation biofuels developed by BDI (BioEnergy International AG) at an industrial pilot plant in the OMV refinery in Vienna/Schwechat in cooperation with the Graz University of Technology. The bioCRACK process applies a liquid phase pyrolysis in which biomass is thermally treated in a heat carrier oil, e.g. vacuum gas oil (VGO) that is a side product of crude oil refining. Researchers at TU Graz claim that they can currently transform about 23% of the used biomass into fuel and the aim is to produce a fuel with up to a 100% biogenic carbon share on an industrial scale by means of hydrodeoxygenation of the liquid-phase pyrolysis oil and they have already been able to achieve this on a small scale. The goal is to make this technology practicable in the current bioBOOST plus project that aims to increase the overall liquefaction yield of biomass to biofuels by continuous catalytic hydrogenation of pyrolysis oil at standard refinery parameters. The final aim is the commercial utilization of the technology for producing high quality liquid biofuels from lignocellulosic biomass with high yield of conversion and continuous operation on an industrial scale.

[9] It is a collaboration between BioEnergy International (BDI) and OMV, also supported by the Austrian Climate & Energy Fund “New Energies 2020”.

Two SET-Plan flagship activities are carried out on the co-processing of bio-oil produced by pyrolysis or direct liquefaction into existing refineries in Finland: one in the **Neste oil Porvoo** refinery and one by Technical Research Centre of Finland, VTT '**Integration to refinery co-feed'**.

Neste oil is investigating different options to extend their feed portfolio, in view of co-processing the bio-oil with their traditional feedstocks. VTT is carrying out an on-going project (EUR 5 million) with the aim of upgrading pyrolysis oil produced from forest residues and waste for integration into refinery co-feed. The integration to highly efficient refinery processes will improve the cost and efficiency of the overall system.

The **bioliq pilot plant** in operation at Karlsruhe Institute of Technology (KIT) in Germany and the **BTG-BTL EMPYRO plant** in the Netherlands already mentioned in section 2.3.3 are also defined as SET-Plan flagship projects.

In the field of hydrothermal liquefaction/HTL, in addition to the projects already mentioned above, the **Hydrofaction** project (2015-2017), including the HTL technology developers Steeper Energy, aimed to move the technology closer to commercialisation, including by adjusting their bio-oil product in order to more closely meet the needs of possible bio-oil users. The project successfully ran a pilot plant and produced extensive engineering plans for a larger demo plant, and produced high-quality bio-oil. Developing the usage of the produced oil appears to be the next step for the partners.

HyFlexFuel (2017-2021) aims to demonstrate the process can be successful with a wide range of feedstocks, improve the fuel production step (the bio-oil itself can be upgraded to hydrocarbon type fuels), and to try and clarify the relationship between feedstock and the specifications of the resulting final fuels. According to the periodic reporting report, the project is going according to the work plan; three feedstocks (miscanthus, sewage sludge and spirulina) were processed in the HTL pilot-scale plant. The bio-crude produced from each of the 3 tested feedstocks appears to have good potential to become drop-in fuel. On the residual streams, good progress was achieved in nutrient recovery.

Other three projects on HTL have recently started: **ABC-SALT** (2018-2022), **NextGenRoadFuels** (2018-2022), and **REBOOT** (2020-2024). **ABC-SALT** will validate at lab scale (at TRL 4) a novel route to produce sustainable biofuels (middle distillates) from various lignocellulosic waste streams. The technical challenges that the project will overcome are: liquefaction and subsequent catalytic hydro-pyrolysis of the biomass in a molten salt environment, followed by the catalytic hydro-deoxygenation of the vapour phase using suitable catalysts to obtain a hydrocarbon product suitable for use as a middle distillates biofuel. **NextGenRoadFuels**' aim is to apply advanced HTL technology and subsequent upgrading to a selected range of low value/cost feedstocks (e.g. sewage sludge, food waste and construction wood waste) to be converted in cost competitive, sustainable drop-in quality synthetic gasoline and diesel fuels. A validated baseline HTL process chain designed for lignocellulosics will be optimized and new innovative process steps will be designed to address the additional challenges related to such feedstocks. **REBOOT** proposes to use the hydrothermal liquefaction (HTL) technology to produce bio-crude from wastewater. The technology will be tested on pilot continuous reactors with the aim to offer a new waste management concept.

ENI in Italy have their **Waste-To-Fuel** pilot plant HTL running at the Gela refinery, it is recognised as a SET-Plan flagship project.

Projects on Thermo-Catalytic Reforming (TCR)

The aim of the **TO-SYN-FUEL** project (2017-2021) is to demonstrate and validate the technical and economic viability of an integrated technology that combines Thermo-Catalytic Reforming (TCR), with hydrogen separation through pressure swing adsorption (PSA) and hydro deoxygenation (HDO) to produce a drop-in biofuels equivalent to gasoline and diesel from industrial organic wastes (pre-conditioned sewage sludge). This project will deliver the first pre-commercial scale plant (TRL 7) that will operate at Rotterdam

Harbour Netherlands Plant One and will process up to 2 ktonnes/y of dried sewage sludge converted into 210 thousand litres/year of liquid biofuels and up to 30 tonnes of green hydrogen. This project, a H2020 IA, is also a SET-Plan flagship project for its contribution to achieving the SET-Plan targets.

4.2.5 Fast Pyrolysis: focus of national and international projects

In EU, research on fast-pyrolysis is on-going mainly in Finland, Netherlands, Norway and Sweden in addition to the SET-Plan flagship projects reported above. In **Finland**, The Finnish Funding Agency for Technology and Innovation (Tekes) is funding a five-year project started in 2014 LignoCat (lignocellulosic fuels by catalytic pyrolysis) carried out by a consortium of three companies (Fortum, UPM and Valmet), as mentioned in section 2.3.3, to develop and commercialize a technology for the production of advanced lignocellulosic fuels by catalytic pyrolysis.

In **Netherlands**, the CatchBio (Catalysis for the sustainable production of chemicals from Biomass) research program on 'Biomass Catalysis' funded under the Smart Mix Program of the Dutch government between 2007-2016 included several projects on different aspects of catalytic pyrolysis involving partners from industry and academia (CatchBio website). Although the consortium is officially closed, it produced a considerable amount of publications, and created a strong network of academia and industry in the field.

In **Sweden**, Bio4Energy is a joint national research program between universities and research institutes funded through the Government's strategic research (Bio4Energy website). The second programme period started in 2017 and will finish in 2021. Bio4Energy produces methods and tools for making advanced biofuels, green chemicals and smart bio-based materials and it includes a platform on 'Thermochemical Conversion Technologies' that has been set up to develop gasification, combustion and pyrolysis processes.

Outside EU, national research laboratories in the **US** (such as the National Renewable Energy Laboratory NREL, the Pacific Northwest National Laboratory PNNL, and the Oak Ridge National Laboratory ORNL) carry out a number of research projects on pyrolysis with the support of the Bioenergy Technologies Office (BETO) of the Department of Energy (DoE). In the framework of the seventh biennial external review of the BETO's R&D portfolio (BETO, 2017), already discussed in the gasification part, external experts reviewed also projects on fast pyrolysis carried out between 2015 and 2017. The reviewers evaluated the work on fast pyrolysis as lacking of evidence for significant breakthroughs that would support an extensive commercial application of pyrolysis liquids as an alternative to oil and suggested to deemphasize research on pyrolysis to a sort of extent. They recognized that fast pyrolysis is a technology capable of efficient biomass deconstruction, but considered the products generated from whole biomass conversion as having little potential to become economically integrated into current fuel supply chains. They suggested that advances to the state of the art for fast pyrolysis should be done by targeting biomass fractions components (various forms of lignin, cellulose, hemicellulose, and extractives) and additional work is required on up-front separations, so that downstream conversions will more likely generate higher-value products. Therefore, fast pyrolysis should move towards a 'downstream' role where more valuable and better-refined products are generated. The integration of new co-reactants into the process to expand or improve the final product was also suggested. Hydrotreating whole-biomass pyrolysis liquid is viewed as unlikely to find wide commercial application while projects looking at alternative hydrogen sources should be encouraged.

In **Australia**, the Australian Renewable Energy Agency (ARENA), announced in 2015 USD 5 million funding for the Renergi pilot scale bio-oil facility in Perth. Following successful testing in a pilot plant, a 100 kg/hr demonstration plant has been designed, built and commissioned (Renergi website).

4.2.6 Hydrothermal liquefaction: focus of international projects

In the **US**, Pacific Northwest National Laboratory (PNNL) in conjunction with the DOE's Bioenergy Technologies Office (BETO) have prioritised the following four areas for their work in progressing HTL technology, namely; (i) testing with continuous flow reactors, (ii) checking yields with specific feedstocks, characterise the biocrudes, and to characterise the biocrudes for use as a refinery blendstock (PNNL, 2017). Licella an Australian company, are beginning to test their technology in a full industrial-scale setting in a **Canadian** pulp-mill, which is a first-of-a-kind (PyNe, 2017), and Altaca/SCF Technologies in **Turkey** have developed a HTL demonstration plant, aimed to use sewage sludge and food waste feedstocks (E4Tech, 2017).

4.2.7 Projects on other thermochemical technologies

One H2020 project has been found with the aim to develop a thermal technology that is different from the technologies considered in this section. **SSOP** (2017-2019) is supposed to be a technology able to valorise the waste sludge from municipal wastewater treatment plants by transforming it into valuable oil and avoiding traditional disposal methods (ocean and land dumping, composting and incineration). The process aimed to transform 95% of the solids in sewage sludge to fuel (oil+gas+char) reducing the disposed sludge volume to 5%. From the published periodic reporting, it appears that the project has focused on the design of the facility.

A SET-Plan flagship project '**RenFuel**' is an on-going project (first phase 2015-2018) in Sweden carried out by the Swedish company Renfuel in collaboration with Preem, Rottneros, Valmet among other partners. The aim of the project is to investigate the use of the RenFuel technology to enable oil refineries to handle lignin-based feeds in their current hydroprocessing units in order to produce standardized gasoline and diesel. The Renfuel technology is a patented catalytic process which converts lignin into renewable lignin oil (LIGNOL®) at atmospheric pressure, below the boiling point, in a matter of hours with 100% yield of a residual raw material according to the company (Renfuel website). Renfuel announced, in a press release (May 2018), that they are planning, in collaboration with Preem and Rottneros, the construction of the world's first lignin plant for biofuel production in Vallvik, Söderhamn (Sweden). The plant is expected to produce an annual volume of 25-30 000 tonnes of lignin and to be completed by 2021.

4.3 Oleochemical technologies

4.3.1 FAME and HVO: focus of H2020 and SET-Plan flagship projects

The FAME and HVO processes have a common issue related to feedstock sustainability. The initiatives supported by EC are practically entirely focusing on the search of new sustainable feedstocks or on improving the yield of the existing solutions.

Several H2020 projects certainly describe that trend. **BioDie2020** (now finished) aimed to improve pretreatment technologies for using degraded waste oils & fats, from waste water company infrastructures, as alternative feedstocks. **SOLARIS** (now finished) aimed to demonstrate the possibility to produce oily feedstock for the HEFA process in EU from non-edible and nicotine-free Tobacco plantations. Another interesting H2020 on-going project is **BIO4A**, which aims to produce sustainable alternative fuels for aviation, via the HEFA process, by sourcing sustainable feedstocks such as UCO, and over the longer term looking at crops grown on marginal land in the EU, principally Camelina. Another on-going project is **FlexJET;** it looks to build a pre-commercial demonstration plant for the production of advanced aviation biofuel (jet fuel) from waste vegetable oil and organic solid waste biomass (food waste).

Algae are a well-known potential feedstock but the experiences carried out so far have not yet been able to demonstrate economic sustainability. A large share of the current algae related projects is focusing on other markets than biofuels. Some projects claim the possibility to produce biofuels but it is clear that the efforts are for producing high-value products for pharmaceutical, cosmetic, food and feed sectors (e.g. **INTERCOME**, **ECO-LOGIC Green Farm**, etc.). These pilot projects have showed the market potential for microalgae, but with limited results for the fuel sector.

Amongst the projects focusing on the biofuel sector, **MACROFUELS** is an interesting initiative, which is trying to implement biofuel production from seaweeds, reducing production costs by improving each step of the chain. Based on the achieved results, the project outcomes showed that realistically, seaweed-derived biofuels could be available in the market by 2030. Other initiatives on microalgae are today focusing on significantly improving the photosynthetic efficiency (**BioMIC-FUEL**, **SE2B** and **SOLENALGEA**), in order to allow cost reductions. but they are at an early stage of development and far from industrial application. The on-going initiatives (SE2B and SOLENALGEA) are positively progressing towards the set goals, while the concluded project (BioMIC-FUEL) showed promising results at pilot scale. For all the analysed projects, the scalabity and techno-economic viability of the identified solutions need still to be demonstrated at relevant scale.

A short summary of each of the investigated projects is provided below:

BioDie2020 (IA) worked on recovering unconventional, degraded waste oils & fats, notably from water company infrastructures, and on demonstrating the conversion of these wastes as a sustainable feedstock for biodiesel production. Key process improvements were reported.

SOLARIS (SME-1) aimed to test a new variety of tobacco plant, specifically targeted to energy applications. The ToboilR (tobacco oil) extracted from Solaris (about 33% of seeds), is a raw material for production of biodiesel, biojet fuel and bioplastic. The overall objectives of the project are: to plan an industrially profitable seed treatment process engineering to apply production in advanced countries; to optimize the overall seed treatment process engineering an automatic harvesting machine; and to strengthen the Solaris value and supply chain.

BIO4A (IA) demonstrates first large industrial-scale production via HEFA process and the use of biojet derived from sustainable feedstocks (initially focusing on UCO), and subsequently investigating the potential of recovery of dry marginal land in Southern EU to grow other energy crops suitable to grow on such land, namely Camelina. The project has reported the successful start-up of a large biorefinery in France, tests in Spain using bio-char to promote carbon sequestration alongside tests on new UCO pre-treatments which are hoped will make the conversion to renewable hydrocarbons more energetically efficient. The project is continuing with its work and is scheduled to end in 2022.

BIOMIC-Fuel (MSCA-IF-GF-Global Fellowships) proposes a bio inspired approach exploiting light-matter interaction by understanding and mimicking the optical properties of corals. The specific objectives are to 1) explore the in vivo light field, optical properties and photosynthetic efficiency of a range of coral species from different light regimes, 2) understand the nanophotonic and structural properties of corals underlying the optimised light modulation and 3) apply the biophotonic insight to design novel photonic materials for the improved growth of microalgae.

FlexJET (IA) is working towards helping the airline sector about binding minimum sustainability targets from 2026 onwards (with some airlines taking commitments from 2022), which effectively establish renewable fuel blending requirements for aviation. It will use food wastes and Thermo-Catalytic Reforming (TCR) (along with other technical processes) to produce 1 200 tonnes of jet fuel from dried organic waste, at a project plant in Germany. The project is progressing, with the first designs for the plant reported as having been made.

INTERCOME (SME-2): AlgaEnergy has recently been able to reach a semi-industrial scale (TRL 7) starting the first phase operations of its semi-industrial plant in South Spain, which captures real flue gas emissions directly from the second biggest combined cycle plant in Europe, being a worldwide premiere. Therefore, AlgaEnergy is now ready to orientate its technology towards the commercialization of its already commercially viable products. INTERnational COmmercialization of innovative products based on MicroalgaE (INTERCOME– the second phase of the SME Instrument project ALGAEPRINT) is based on the commercial orientation that is needed to make AlgaEnergy financially autonomous, after millionaire resources and 8 years of efforts invested in applied R&D.

MacroFuels (RIA) aims to produce advanced biofuels from seaweed. The targeted biofuels are ethanol, butanol, furanics and biogas. The project will demonstrate a biomass yield of 25 kg seaweeds (wet weight) per m^2 per year harvested at 1 000 m^2/hr. Partners also claim to be able to improve pretreatment and storage of seaweed and to yield fermentable and convertible sugars at economically relevant concentrations and to increase the bio-ethanol production to economically viable concentrations and bio-butanol yield.

SE2B (MSCA-ITN-ETN) goal is to optimize the conversion of Solar Energy into Biomass (SE2B). The SE2B network deals with this optimisation in an interdisciplinary approach including molecular biology, biochemistry, biophysics and biotechnology. SE2B will provide information on the similarities and differences between cyanobacteria, green algae, diatoms and higher plants, the organisms most commonly employed in biotechnological approaches exploiting photosynthetic organisms, as well as in agriculture. The knowledge gained from understanding these phenomena will be directly transferred to increase the productivity of algal mass cultures for valuable products.

SOLENALGAE (ERC-STG) aims to improve solar energy conversion of biomass, considering that only 45% of the sunlight covers the range of wavelengths that can be absorbed and used for photosynthesis, the maximum photosynthetic efficiency achievable in microalgae is 10%. On these bases, a photobioreactor carrying 600 l/m^2 would produce 294 tonnes/ha/year of biomass of which 30% to80 %, depending on strain and growth conditions, being oil. However, this potential has not been exploited yet, since biomass and biofuels yield on industrial scale obtained up to now were relatively low and with high costs of production. The main limitation encountered for sustained biomass production in microalgae by sunlight conversion is low light use efficiency, reduced from the theoretical value of 10% to 1-3%. The project aims to investigate the molecular basis for efficient light energy conversion into chemical energy, in order to significantly increase the biomass production in microalgae combining a solid investigation of the principles of light energy conversion with biotechnological engineering of algal strains.

ENI- GELA (SET-Plan flagship project) aims to create a Green-diesel production section in the ENI-Gela refinery. The nominal capacity of the new plant will be 530 ktonnes/y. The new plant will be flexible with respect to feedstock thanks to a new pretreatment section. ENI is also investing in the upgrade of the Venezia Porto-Marghera plant, to increase the green-diesel production capacity to 560 ktonnes/y.

4.3.2 FAME and HVO: focus of national and international projects

In **Spain**, ECOPRIBER and INMASA developed and patented two new processes for the production of biodiesel. The first method uses methyl acetate and produces no glycerine byproduct rather the molecule triacetin, said to have much higher value. Their second method improves the efficiency of the conventional FAME processes. These technologies enable higher production and profitability ratios with investment, operation and maintenance costs notably lower than those required with current technologies. In Germany, the Greasoline process, which converts waste oils and fats to hydrocarbons has been developed by the Fraunhofer Institute, which aims to build a 10 000 t/per annum demo plant with this technology.

In the **US**, a novel enzymatic biodiesel production processing plant, supported by a DoE grant had been in operation but ceased in 2014 (Piedmont Biofuels, 2018). Wake Forest University in North Carolina developed a sugar-based catalyst said to enable more cost-effective conversion of low quality waste fats into biodiesel although this has not appeared to have developed significantly. US HVO sector appears dynamic and significant investments are on-going, ensuring sector perspectives for the medium term. The current potential, on the base of the DOE-BETO data, can be estimate in 1.8 Mton/yr of HVO/HEFA (DOE, 2017).

TransBiodiesel **in Israel** developed enzymatic transesterification and they claim to have 6 pilot plants using this technology worldwide with at least supposed to be at industrial scale; however, the present status of this plant is unclear (Transbiodiesel, 2018).

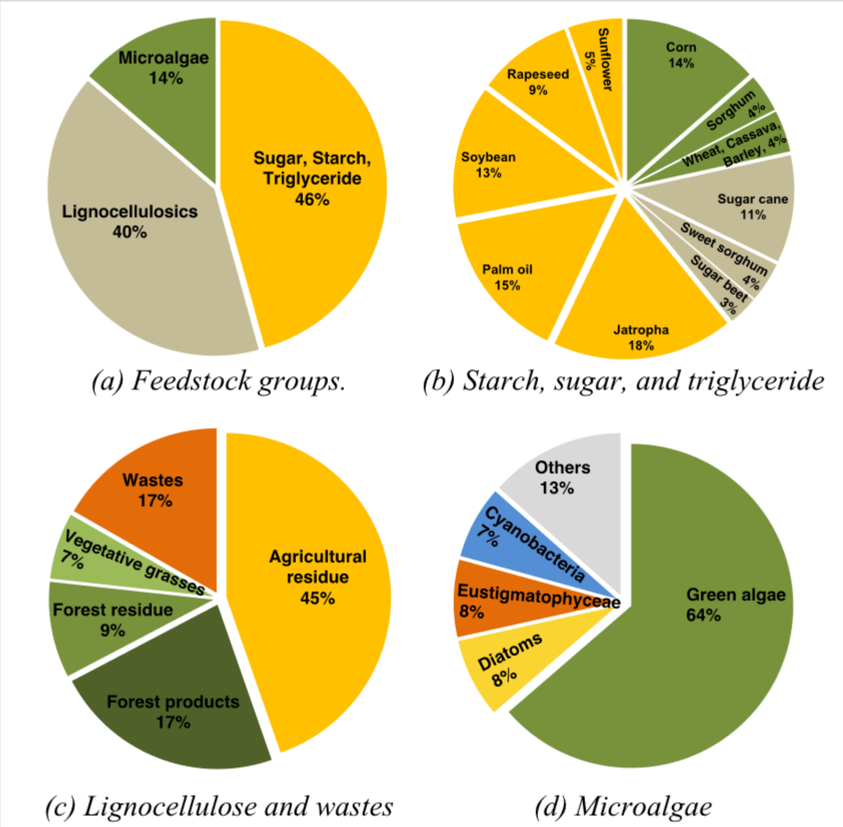
Many companies, based in US and EU are looking at Asia as a significant market for medium and long term; investments in new plants are already established: for instance, Neste Oil is producing exclusively renewable NExBTL since 2015 and new production lines are foreseen (Neste, 2018).

Sinopec in **China** (and Petrobras in Brazil) are new players with a current limited production capacity (Greenea, 2017), but they are expected to strongly influence the sector in the near future. Little information or focus appear to be on biodiesel production in China (USDA, 2017a) and the market value of biodiesel is currently low (Tan, 2018). Certainly, China has more interest in ethanol production and has a mandate for its use as a fuel. Nonetheless, biodiesel initiatives are underway aiming to: improve the existing FAME process' adaptability to handling raw materials (i.e. make it more robust), reduce the energy costs, improve the low temperature properties of the biodiesel, and improve the currently weak market acceptance of FAME in China (Tan, 2018). Investigations are underway into more novel processing approaches such as using the supercritical method of biodiesel production, and investigating enzymatic processes; this, in particular, is considered as promising towards reducing the emissions of waste (water or traditional catalyst) from the process and possibly lower energy requirements.

TEXT BOX 2: Research trends in literature

Some relevant information on research trends on advanced biofuel technologies has been found in a review paper. The review study carried out by Azadi et al. in 2017 analysed more than 49 000 relevant papers on biofuel technologies. They show that most of the published research related to feedstocks published from 1990 to 2014 deals with conventional, edible feedstocks (46%), while lignocellulosic (including wastes) and algal biofuels represent 40% and 14% of the literature respectively. Production of biofuel from oily crops covered about 60% of the literature, while the rest of the papers are almost equally distributed over bioethanol from starch and sugar crops. Jatropha and palm oil were the most widely studied feedstocks within this group, while other highly studies feedstocks included corn, soybean, sugarcane, and rapeseed.

Figure 20. Share of different types of feedstocks in biofuel literature by number of paper (1990-2014) taken from Azadi et al. (2017), Fig. 7



5 Technology development outlook

5.1 Technologies trends and needs

The production of sustainable advanced biofuels requires advanced processes that are currently under pre-commercial, demonstration, or earlier stage of development in a number of plants all over the world, as discussed in the technology state of the art section. Fully commercial production of second-generation biofuels routes is still limited since the production costs are too high and technical barriers have to be overcome.

A number of technological trends are observed in each sector to address key constraints and needs of biochemical, thermochemical and oleochemical conversion paths, as summarized below:

- **Fermentation**: a trend in development of cellulosic ethanol production has been towards projects seeking to show the (and indeed improve) the overall production chain; important to demonstrating the viability of these pathways. A future developmental need is improving fermentation and thus increasing ethanol yields. Moreover, a significant trend will be the guided technological improvement towards finding yeasts that can use C5 and C6 sugars. Material development and needs involve novel enzyme systems from alternative producing strains and catalysts (at reduced costs), as well as advanced solvents in which reaction, separation or hydrolysis can take place (e.g. green solvents, Ionic Liquids). Overall, future trends and needs in fermentation will include optimization of new processes by developing better economic and environmental performances;
- **AD**: anaerobic digestion current trends can be summarized by the following points:
    - o Improve the management of the digestate produced by the plant, including the application of new technologies for a direct nutrient recovery. Several projects are investing solutions to use digestate as a substrate to recover building-blocks for biomaterials production.
    - o Improve AD performances, with the clear focus of increasing digestibility of complex feedstock rich in cellulose and lignin. This is currently being performed by testing advanced pretreatments (i.e. cavitation, ultrasounds, etc.) and/or by integrating the AD plant with other processes, mainly based on fungi.
    - o Demonstrate economical performance of biogas upgrading to biomethane, especially for technologies able to produce LNG.
    - o Scale down AD technology, with the aim to increase the use of waste streams at urban level, such as: organic fraction of MSW, residues from milk and beverage productions, etc. The target of such projects is to demonstrate the economic sustainability of the scale-down process, more than solving technical issues.
    - o Coordination and support action projects are also working to enhance public acceptance of AD plants, in order to increase the potential market penetration of scaled down plants. Moreover, several projects are stressing the need of stronger AD integration with other sectors, namely waste management and waste water treatment.
- **BtL and SNG**: both gasification and FT synthesis are well-established technologies for large-scale fossil fuels applications. However, the use of biomass feedstocks and biomass-derived syngas remain technically challenging and many attempts/projects/plants have not been so far successful. Key technical developments are still needed and under investigation in order to improve gasifier performance able to handle heterogeneous feedstocks, as well as the efficiency of the production of high-quality syngas required by downstream processes. In addition, cheap, selective and stable FT catalysts for selective production of specific

biofuels and chemicals are required in relation to the syngas composition. Optimization of the whole process at smaller scales, energy integration and co-processing of FT products at existing crude oil refinery sites are considered as developments able to improve the economic performance of the process.

SNG production via biomass gasification shows similar technical barriers as BtL. Apart from the issues related to catalysts, affected by gas cleaning performances, achieving a stable syngas composition is still challenging. The cancelling of the GoBiGas project clearly indicates there are difficulties in achieving positive economic performance from this technology. Despite this set back, another large-scale initiative (AMBIGO) is coming on the scene, supported by industrial companies. Notwithstanding the difficulties encountered by SNG from biomass gasification, the methanation process itself is still considered as a promising technology, especially in view of the power-to-fuel pathway.

- **Pyrolysis**: the focus on pyrolysis has been on improving the bio-oil quality and the impact on downstream processing, scaling up reactor technologies, improving bio-oil stability, decreasing solids produced and bio-oil moisture content. However, despite the claims of several interesting on-going initiatives, the full integration of fast pyrolysis with upgrading is still required and many of the upgrading processes are still at TRL 3-4.
- **HTL**: trends in HTL biofuel involve the development of continuous-flow catalytic liquefaction technology and to test the potential viability of liquefying different biomass feedstocks, such as radiata pine, miscanthus and algae. To this aim, HTL pilot plants are being developed by Licella/Ignite Energy Resources in Australia, among others. Overall, the technology trends in HTL development include challenging process improvements to maximise the yield of produced bio-oil while minimising the related costs of production that may be derived by the minimization of organics loss to the water phase leading to improved final products yields. More focus on attempting to fine-tune feedstock type and specifications, in order to create a more usable or easier to upgrade bio-oil is evident in recent work, it is not simply enough to produce an oil which may be overly-challenging to use.
- **FAME/HVO**: Initiatives like the Total La Mede start-up, ENI Gela revamp and Porto Marghera scale-up are interesting also from the technological point of view but they are not expected to improve the TRL, which can already be defined as 9. For FAME processes, there has been some focus on improving the uses and value of the glycerine by-product, which can currently be considered to be somewhat in an over-supply situation. Other initiatives aim to reduce costs by developing processes within the overall system, namely by reducing energy input needs. While still not at industrial or near TRLs, as soon as any of these technologies reach high TRLs and begin to generate cost/energy savings, they can be expected to proliferate significantly. As FAME is quite an industrially established technology, developing more sustainable feedstocks remains a priority for this pathway, and for HVO.

5.2 Technology foresight

The JRC-EU-TIMES model offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050. The model was run with three baseline scenarios:

- Baseline: continuation of current trends: it represents a 'business as usual' world in which no additional efforts are taken on stabilising the atmospheric concentration of GHGs; only 48% CO_2 reduction by 2050.
- Diversified: usage of all known supply, efficiency and mitigation options (including CCS and new nuclear plants); 2050 CO_2 reduction target of 80% is achieved.
- ProRES: 80% CO_2 reduction by 2050; no new nuclear plants; no CCS.

In all scenarios, the wood availability is constrained on the basis of the proposals for new LULUCF regulation considering historical use values as maximum future cap.

In addition to the three main scenarios, a further 13 sensitivity cases were run. Nijs et al., (2018) explains the main features of the model and presents all the scenarios and the overall results.

In this technology development report, we focus on the three main scenarios and on one specific sensitivity scenario where the targets of the SET Plan are taken into account (ProRes_SET Plan). For this scenario, an overview of the assumptions (on efficiency improvements and cost reductions) for each technology is provided in (Nijs et al., 2018). The SET Plan scenario is considered to give a foresight perspective since the SET Plan targets steer research and innovation, by leading to new or improved technologies at lower costs.

Figure 21 shows the total amount of biofuels, including first and second generation (in PJ), used in the transport sector for the three main scenarios for 2010, 2020, 2030, 2040 and 2050. The model estimates a share of around 10% of biofuels on the total energy used in the transport sector for 2050 in both the Baseline and the Diversified scenario, which increases up to 20% in the ProRES scenario in the same year.

Figure 21. Final energy use of biofuels in transport sector for three main scenarios

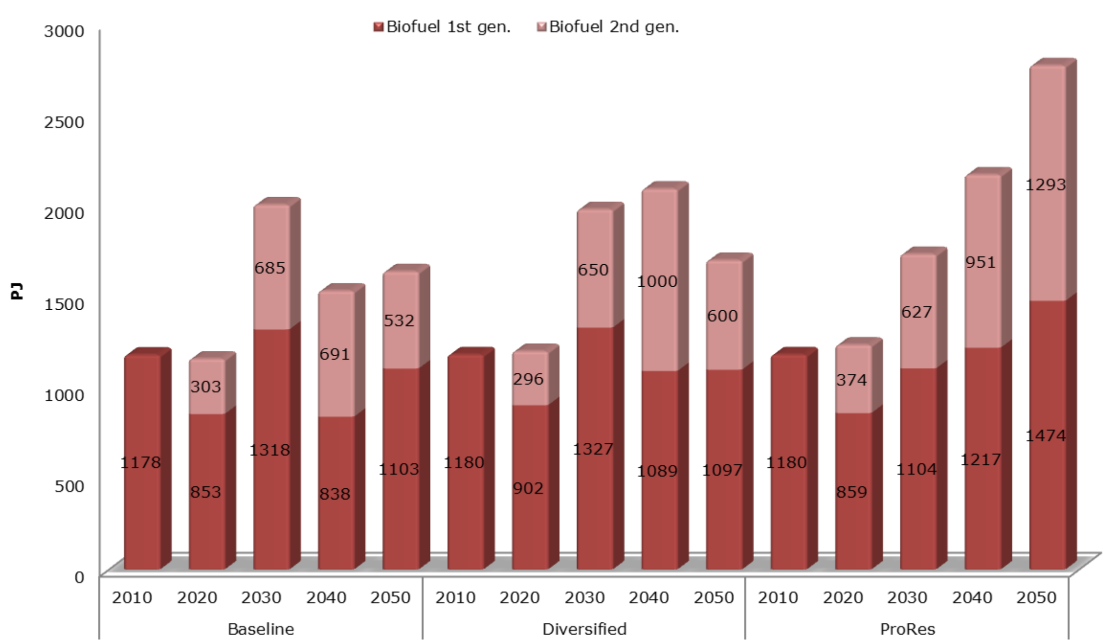


Figure 22 indicates the evolution of the use of biomass in the three main scenarios for the production of first generation and second generation biofuels for different time periods, while Figure 23 shows biofuels imports for the same scenarios.

First generation biofuels are not produced in EU after 2020 in all scenarios, while the amount of biomass used for second generation biofuel increase in the scenarios and over time, contributing to the decarbonisation of the energy sector from 2020. The production of first generation biofuels in EU is phased out since they are not an optimal solution due to their low performance in terms of yields (compared to for example sugar cane ethanol or palm oil); they will be replaced by the production of second generation biofuels and by biofuels imports (Figure 23) which are assumed to be cheaper and more sustainable and more efficient to decarbonise the energy system. This phasing out is in line with RED II that only sets a maximum cap on its use (IINAS, 2014).

However, some first generation biofuels appear to be produced again in the ProRes scenario in 2050. This is because of the combined effect of the 80% reduction target and the CO_2 storage not being allowed: the two constraints push the model to use further CO_2 free sources. The higher CO_2 price makes profitable by 2050 to produce first generation agriculture-based biofuels to help decarbonising the transport sector.

Figure 22. Biomass used for biofuels production in three model scenarios

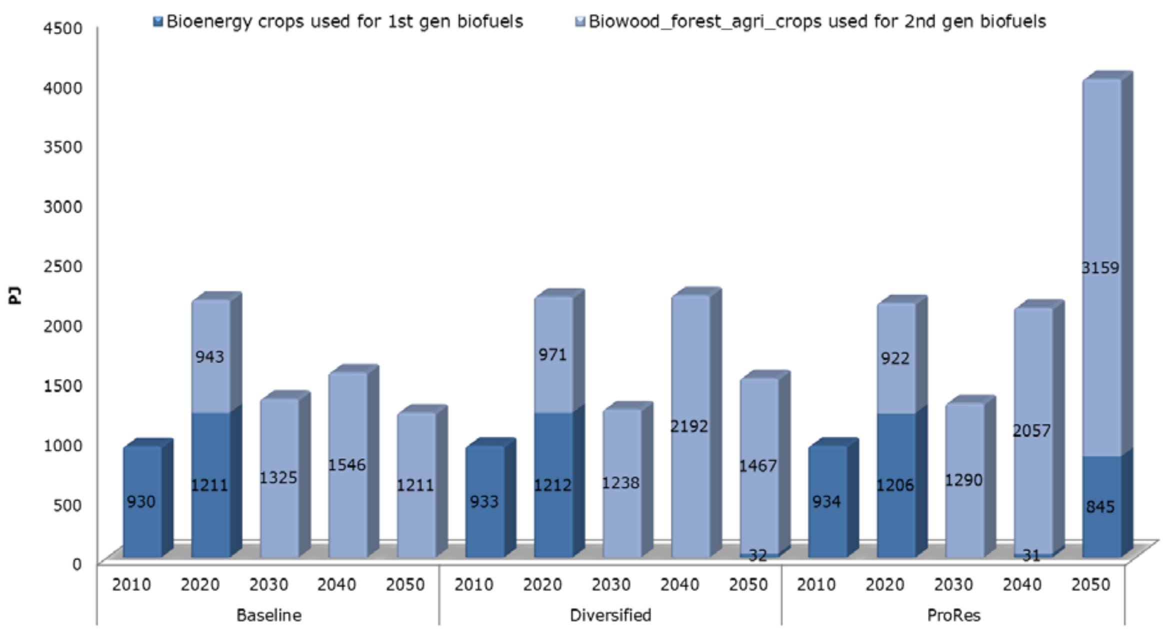
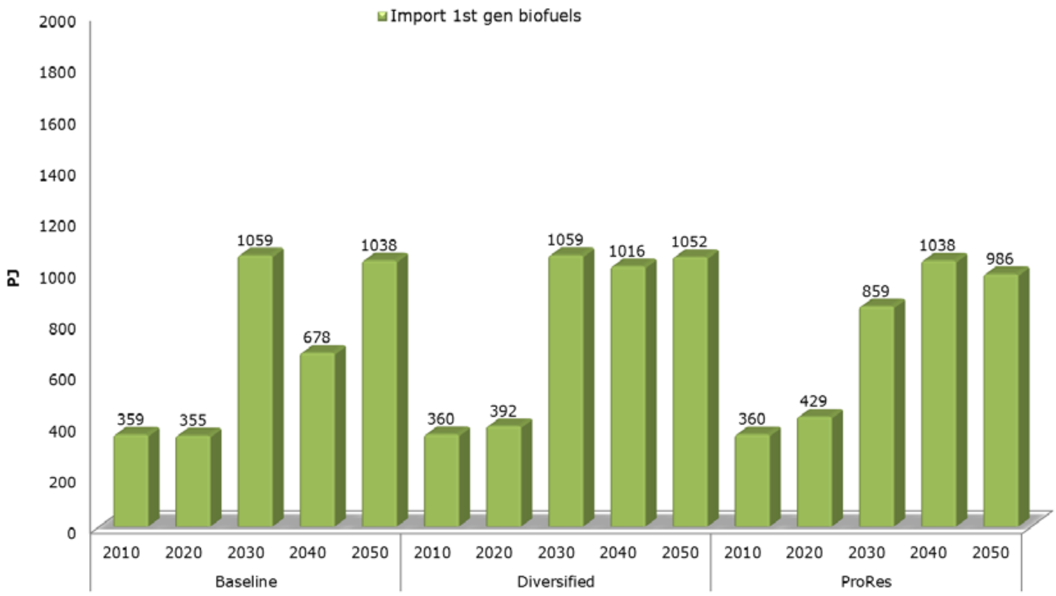


Figure 23. Imports of biofuels in three model scenarios



As explained above, the SET Plan scenario considers the same assumption as in the ProRes scenario taking also into account the SET Plan targets in terms of efficiency improvements and cost reductions. Figure 24 shows that the consumption of advanced biofuels in the SET Plan scenario increased more than in the ProRes scenario in 2050. This means that the improvement in the efficiency of the processes and cost reductions help to increase the use of advanced biofuels substituting less sustainable first generation biofuels; the overall share of total biofuels (including first generation) remained the same in the two scenarios (around 20% in 2050). This result is also reflected in terms of biomass use when comparing the two scenarios; the total biomass use in the SET Plan scenario decreased due to improvement in the efficiencies of the processes and more biomass dedicated to the production of advanced biofuels is used in the SET Plan scenario compared to the ProRes scenario (Figure 25).

Figure 24. Final energy use of biofuels in transport sector for the SET Plan scenario

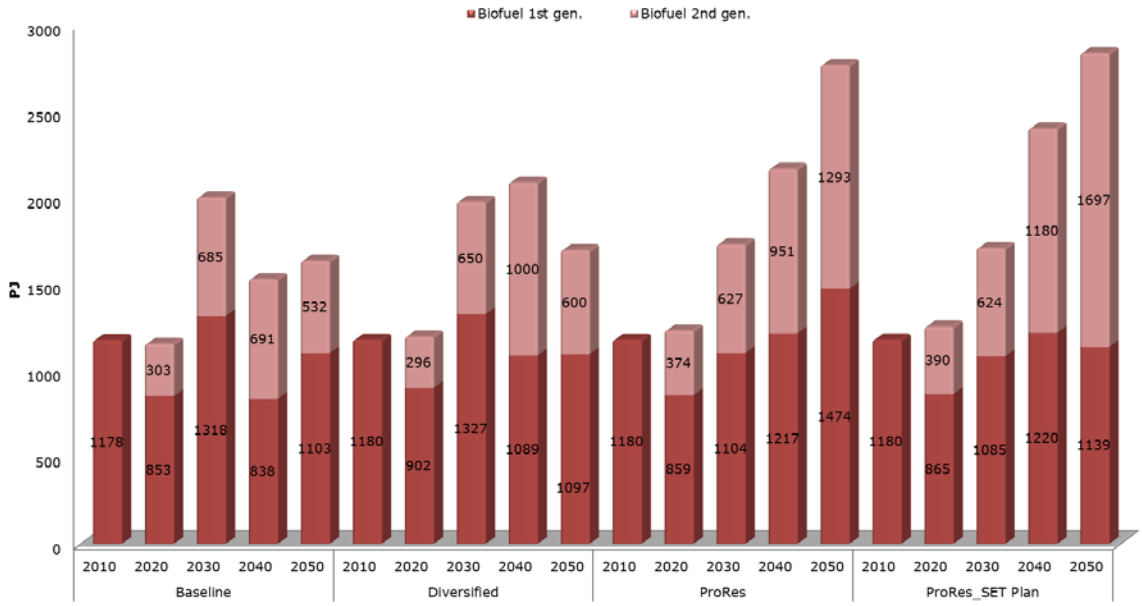
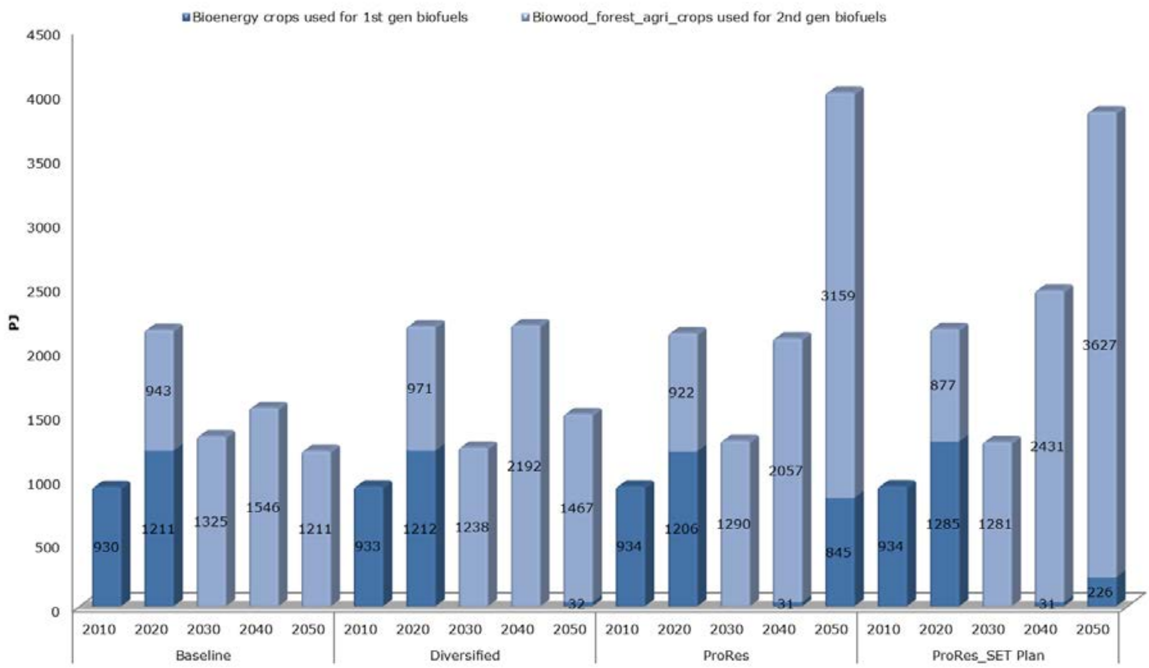


Figure 25. Biomass used for biofuels production for the SET Plan scenario



5.3 Technology barriers to large scale deployment

5.3.1 Biochemical technologies

5.3.1.1 Fermentation

Some developers see the adaption of microbes to use lignocellulose and other second generation sugars as relatively straight-forward, and that the ability to consume C5 and C6 sugars can be achieved in a few years. However, the primary challenge of using second generation sugars stems from the use of real-world feedstocks; the variability in quality and composition of second generation sugar hydrolysates, plus the presence of new inhibitors from integrated pretreatment processes can dramatically lower microbe yields (E4Tech, 2017). Overall, the development of both energy and cost effective pretreatment, hydrolysis and fermentation, remain the challenges hindering large scale deployment of lignocellulosic biomass conversion to ethanol.

In practice, the number of **substrates** used in pilot and demonstration plants for biofuels production remains small, therefore continued R&D is needed to widen the substrate basis, i.e. a narrow feedstock choice can be seen as a technological barrier which could be overcome by investigations which help diversify the available feedstocks. This work would identify optimal substrate mixture selections. It would allow the inclusion of (i) substrates such as grass or straw, woody material or certain wastes which may contain or produce substances toxic for the bacterial flora in fermentations, or (ii) those substrates which are not sufficiently accessible for the degrading microorganism or enzymes. Cost and energy efficient pretreatment and separation schemes are required. A major challenge is to ensure that all biomass input components as well as the by-products are utilised in an optimal way. Pretreatment schemes ensuring optimised use of the biomass continue to be developed. Raw material flexibility, minimum inhibitor formation, as well as maximum carbohydrate yields are central targets. The fate of lignin and hemicelluloses are important challenges to be overcome. Processing has to avoid unfavourable conditions for sugar re-formation (back-reaction), chemical derivatisation (pentoses to furfural, lignin to sulfo-lignin, formation of lignin-carbohydrate complexes) and physical change.

Lignin can be a high value raw material suitable for conversion into a variety of products for which a lot of research has been done. An effective **separation process** for the biomass constituents, following pretreatment, remains as a challenge. The separated raw material constituents (such as lignin and extractives) can be further converted to value-added products. Fermentation broth as well as solid residues (including bacterial/yeast cell mass) are nutrient rich and can be returned to the process, used as feed for animals, or added to biogas plants.

To improve enzymatic **hydrolysis** efficiency, cheap ways of production (such as enzyme production on site without enzyme purification; the cost of enzymatic hydrolysis accounts for 30-50% of the total cost of ethanol production) and new types of cellulases are being studied, such as bacterial enzyme complexes. The precondition is a dramatically improved technology for enzyme screening and production of heterologous recombinant proteins using new genetic material. Screening for new enzyme activities is severely hampered by the lack of a range of host organisms with available genetic tools. For a systematic search for new, effective thermophilic cellulolytic enzyme systems, new platform organisms for protein expression and genetic engineering have to be added. Possibilities for enzyme reutilisation are also being studied, e.g. by applying novel magnetic nanoparticles (small size) loaded with enzymes. Expression of recombinant enzymes at large scale is a major challenge. Research into modification of alcohologenic strains for polysaccharide degradation in one vessel (“consolidated bioprocessing”) is on-going. There is no theory of enzyme activity on insoluble substrates/surfaces which hampers progress towards material savings through improvement of hydrolytic enzymes.

For **fermentation**, ethanol production from sucrose is a traditional fermentation process effectively performed using yeasts such as *Saccharomyces cerevisiae*. However, the effective conversion of lignocellulosic raw materials, which containing varying sugar mixtures depending on raw material input (e.g. C5 and C6 sugars) is more challenging (i.e. it needs to be more robust, capable of fermenting C5 sugars). Thus, there is a need to further develop microorganisms capable of effective conversion of lignocellulosic biomass inputs. Novel enzyme mixtures must be developed or novel microorganisms capable of simultaneous hydrolysis and fermentation (SSF) must be developed. More natural organisms have to be screened to identify appropriate strains of bacteria or fungi (mainly yeasts), or to isolate genes with more appropriate enzymatic or metabolic functionality that will enlarge the substrate basis and product range, and increase production efficiency, as well as decrease the amount of material needed.

Simultaneous utilisation of pentose sugars by highly effective industrial **yeast strains** is still a challenge in developing continuous fermentation. Alternative alcohol producer organisms such as the bacteria: *Escherichia coli, Klebsiella oxytoca, Lactobacillus sp., Clostridium sp.* and others are developed for the simultaneous utilisation of all sugars (pentoses as well as hexoses). The tolerance of ethanol producing bacteria for high substrate, inhibitor and product concentration needs to be improved as well. For newly isolated species and strains, genetic systems have to be evaluated and developed. Alcohol producing strains with the ability to hydrolyze polymeric substrates are in the pipeline. A major challenge is the metabolic engineering in industrially successful yeasts and in promising bacteria, especially regarding the redox balance and carbon flux. High end product concentration and selectivity, and insensitivity to inherent and generated inhibitors and process conditions remain major goals. Development of effective thermophilic fermentation organisms would reduce the need for cooling media, the risk of contamination by competing microorganisms during the fermentation process, reduce the viscosity of the medium thus facilitating more effective mass transfer processes, as well as aiding downstream separation. Isolation/development of robust microorganisms, both with respect to fermentation inhibitors as well as to substrate or product inhibition represents another favourable advantage. High dry matter concentration in the fermentation process is also desirable as this will give high product concentration and help product recovery from fermentation liquor. This could be achieved by developing novel process layouts involving for example systems aimed at immobilisation of the fermenting organisms by the advanced use of non-fouling membrane systems, encapsulation of the organisms in polymer beads, etc.

Effective product separation is another advantage of advanced fermentation set-ups. This could also represent a step in the direction of a transfer from the current batch-wise into continuous fermentation processes which would represent a more effective conversion. Optimisation of the fermentation media (nutrient mixes adapted to the fermentation organism) is needed for fast and effective bioconversion of different substrate inputs. In order to develop SSF processes, microorganisms capable of both enzymatic hydrolysis of the substrate as well as fermentation of the sugars are needed (whole cell catalysts).

Downstream processing of products requires advances in membrane or adsorbent technology. One challenge is effective separation of higher alcohols from water. There is a need for membranes with high removal capacity of product, e.g. for pervaporation, or suitable absorbents. Separation and rectification technology is most demanding and needs further research on materials (membranes, adsorbents). If recombinant bacteria are used in the process, the residual material has to be deactivated.

5.3.1.2 Anaerobic digestion

Anaerobic digestion is a well developed sector across Europe (and when compared with other non-EU countries), and several countries have already achieved significant production capacity, namely Germany, Italy, France, UK and The Netherland. For large and medium scale plants, the current barriers can be identified in the feedstock supply. The availability of sustainable feedstock is clearly an issue for plants, especially with respect to the possibility to find materials not used by other sectors, in order to have the possibility to limit costs and price volatility. Anaerobic digestion plants are typically quite flexible with respect to feedstock but the methane yield, from materials containing high quantities of cellulose and lignin, or more heterogeneous as MSW, has still rooms for improvement.

The digestate management is another key-point for the future deployment of the sector; in particular, the current research is focusing on alternative ways of valorisation, by means of direct nutrients extraction and utilization for the production of bioplastics and other biomaterials.

Along the AD plant pipeline, a key step is today represented by the biomethane upgrading section. It is clearly recognised that biomethane production is a target for the short-medium term. A relevant number of projects are currently already demonstrating the technical viability of upgrading technologies, but their economic sustainability has still to be proven. Subsidies in the form of investment grants and/or feed-in tariffs are today supporting investments, particularly for small farm-scale plants. This is particularly true for technologies, such as cryogenic separation, that are of particular interest as they are able to directly produce LNG for transport. The potential integration of AD plants with other sectors, such as waste management, could allow properly sizing the plants to become economically more sustainable.

The scaled down AD plant process is also interesting, in order to increase AD market penetration and better valorisation of waste streams at the urban level. Nevertheless, the current public acceptance of this technology does not necessarily allow building plants in such a context and actions on this side are still needed.

5.3.2 Thermochemical technologies

5.3.2.1 Gasification with Fisher Tropsch for BtL production

The development of low-cost and high-efficiency FT processes remains a major barrier for the establishment of large-scale BtL production from biomass.

Existing FT technology commercially operating using fossil feedstocks are at very large scales that are not suited to biomass posing problems of feedstock availability, supply logistics and costs and preventing possible large-scale BtL development. The required volumes of feedstocks might be large enough to compete with other uses or require long transportation distances and as a consequence significantly increasing costs. Hence, the availability of a low-cost biomass supply and the development of processes which are efficient at smaller scales are among the major challenges for the potential development of BtL plants (IEA, RETD, 2016).

Technical advances in the conversion efficiency of biomass into syngas, as well as syngas conditioning and upgrading may improve the overall process performance and contribute to reduce both the capital and operating costs of BtL installations.

Work is still needed to prove reliable long-term operation of the different gasifier types at scale using a variety of feedstock input while still providing the syngas requirements necessary for downstream applications. The optimisation of gasifier conditions and specific syngas compositions as well as the efficient thermal integration of the various steps of biomass handling, gasification, syngas clean-up and FT synthesis have been identified as major challenges in recent reports published by IRENA and E4Tech (IRENA, 2016 and E4Tech, 2017). The clean-up of syngas to remove impurities, such as tars, particulate matter and pollutant gases (ammonia and sulphur gases) has been subject of several investigations. However, especially tars remain a key problem, and several high temperature tar cleaning options are under development (such as hot gas clean-up via thermal cracking; tar cracking using plasma, multi-stage oil scrubbing; catalytic tar removal). Energy efficiency can be improved using syngas clean-up technologies that operate at high temperatures avoiding thermal energy losses from syngas cooling and reheating or integrating processes. The development of high temperature sulphur removal technologies (sorbent-based or membrane technologies) might also contribute to efficiency improvement (IRENA, 2016).

For the downstream catalytic production of BtL fuels, the design and preparation of active, more selective and stable catalysts for the production of required fuels fractions have an influence on the process performance. However, FT catalyst performance and lifetimes are considered as a less significant barrier if integration and syngas clean-up are successfully implemented (E4Tech, 2017).

5.3.2.2 Gasification with methanation for SNG production

In section2.3.2, the current situation of EU projects and initiatives has been widely described. The stop of the most significant project (GoBiGas) clearly highlights the problems that the sector is facing. The costs for running the plants have been defined, by the GoBiGas plant owners, as the main barrier. Differently from the most of the bioenergy applications, i.e. HEFA, cost problems are in this case related more to the process than to the feedstock. The high costs for managing a gasification plants are known, and common to the BtL projects. For SNG, the costs associated with the short lifetime of the catalysts are today the main specific barrier; this has to be linked with the technical barriers limiting the diffusion of the gasification technology (i.e. capability of producing a clean syngas at a reasonable cost for the plant operator). Apart from issues related to catalysts, which are affected by gas cleaning performances, achieving a stable syngas composition is still challenging.

A conclusion that can be drawn is that, in order to see a real development in this technology, there is a need for cheap, selective and stable methanation catalysts, able to allow effective SNG production with the peculiar biomass derived syngas composition. Unfortunately, with the exception of the AMBIGO initiative, the current investment trend seems to have been shifting toward the production of SNG with power-to-gas technology instead of by syngas pathway.

5.3.2.3 Fast Pyrolysis

The main barriers for the widespread application of fast pyrolysis include both technical and economic considerations that make the technology currently exploited only for heat and power applications.

The main technical barriers relate to bio-oil production and upgrading as well as their integration; the low bio-oil yield has an impact on production costs, making the process still not really attractive from an economic point of view.

The major problem with bio-oils produced from pyrolysis is typically their unfavourable characteristics (particularly high water and oxygen content and low thermal and chemical stability) that make not only storage but also downstream processing problematic. The potential of upgrading bio-oil into drop-in transportation fuels has not been validated at large scale and more efforts are still needed.

Pretreatment processes to decrease the ash content of biomass feedstocks and produce better quality pyrolysis oil are also areas under investigation (IRENA, 2016) as well as ways to improve bio-oil quality and yields by reducing chars, alkali metals and water content.

The major concerns for bio-oil upgrading are the water and oxygen content that are higher than crude oil (Karatzos et al., 2014). For co-refining processes, this will damage the catalysts and reduce the yield of the final products. Oxygen content can be reduced with hydrodeoxygenation, which requires a hydrogen source. The IEA suggests the limited availability of low cost and sustainable hydrogen as a further significant hurdle (Karatzos et al., 2014) and the hydrogen requirements of the multiple hydroprocessing steps commonly used make the bio-oil upgrading unattractive significantly impacting on the overall production cost.

Significant research on catalysts and reactors is still needed as well as ways to reduce the hydrogen consumption are essential to reduce operating cost for upgrading bio-based feedstocks via hydroprocessing.

5.3.2.4 HTL

Currently, HTL of biomass feedstocks to hydrocarbon liquid fuels is under development at the lab/bench-scale levels with the exception of Licella (PyNe, 2017) that appear close to industrial-scale production through integrating their HTL technology within an existing working paper mill. They state their bio-oil will be stable; how it performs under refinery upgrading will be critical. There remains limited information available on continuous-flow tests, which would help can provide a reasonable basis for process design and further scale-up for commercialization, while there is considerably more major information is derived from batch reactor tests. While several feedstocks have shown favourable results in terms of energy recovery and carbon efficiencies, there are still a number of challenges which need to be addressed before the technology can be developed to demonstration scales of operation, both in the production of the bio-oil production and its subsequent upgrading to liquid hydrocarbons. To achieve the above, specific challenges remain to be addressed, namely; reducing capital costs by moving away from a stirred-tank reactor configuration to a scalable plug-flow reactor configuration, improve the ability to pump high concentration slurrys while operating at high pressures in the hydrothermal system, both of which may lead to capital cost reduction, and understanding/developing appropriate materials of construction for process design (which can withstand corrosion problems and high pressures). The ability to dispose relatively high volumes of waste water is another area which requires more work. A more large-scale issue is that of successful upgrading of bio-oils to liquid hydrocarbons at oil refineries. A review of Elliott et al. (2015) on HTL of biomass lead to the conclusion that there is potential for commercialization of the technology, and techno-economic calculations highlight promising results especially for wet waste and algae feedstock.

5.3.3 Oleochemical technologies

5.3.3.1 Transesterification of residual/waste oil and fats

The transesterification of waste oils and fats can already be considered large-scale, with several million tonnes of this non-food waste-feedstock biofuel being produced annually in the EU (though the authors note there is disagreement over the definitions of what constitutes a waste feedstock). Nonetheless, within this pathway, there are new developments which, if integrated and put into large-scale use, would likely help improving the overall efficiency or costs. Although it appears there is some scope for expanding the volume of UCO recovered in Europe, there is a strong need to further expand the available **waste feedstock resource** – possibly through better recycling -and thus increase the volumes of waste biodiesel production. R&D to identify new sources of waste oils and fats, or indeed to develop pretreatments or processes available to handle fats and oils which traditionally have been seen as challenging to process, is needed. Although not strictly a barrier to its further deployment, work on valorising or finding other uses for the large volumes of **glycerine by-product** from FAME, would benefit the economics of the overall process. Demonstration of performance at pilot/demo scale of novel **heterogeneous catalysts** would be important to improving their industrial credibility.

5.3.3.2 Hydroprocessing of residual / waste oil and fats

The current HVO production in EU and US shows that no major barriers, to large scale deployments, are due to technological limits for vegetable or animal oils and fats. Indeed, most recently, a large increase in production capacity in the EU has been noted. A barrier to market deployment is instead the cost, or securing sufficient levels of supply of sustainable feedstocks. In the last decade, significant efforts have been engaged by industry and the research community to search for sustainable and economically viable alternatives, but significant improvements would still be needed to achieve market competitiveness with current fossil products.

If the feedstocks are not oil and fat type, there remain technological challenges for the HVO/HEFA industry related to the co-processing of what are more complex feedstocks, namely biocrudes from fast pyrolysis and HTL. The principle challenges concern pretreatment technologies (in order to try and obtain a uniform material for co-processing) and to improve catalysts' duration and overall performance when processing these non-fossil feedstocks.

6 Conclusions & Recommendations

The analysis of the outcomes and goals of the EU H2020 EU projects as well as SET-Plan flagship projects and international research program and activities, discussed in previous sections, bring to the following conclusions and recommendations for future priorities on each advanced biofuel technology analysed in this report. The conclusions of this report are the same as the 2018 report.

6.1 Biochemical technologies

6.1.1 Fermentation

The focus of a considerable share of the H2020 projects on fermentation is on proving the robustness of the entire cellulosic ethanol production chain, which is a very welcome approach. While some projects are at a large scale, others aim for production at smaller scale, and it will be very interesting to see the eventual results and progress of these key projects. However, at the time of writing the report, for still on-going large-scale projects like LIGNOFLAG and BIOSKOH, no information has been found on their progresses. Even if overall steady and reliable production is not achieved, it will be important to understand any remaining weak points and to focus further research efforts on these. Notwithstanding the encouraging work towards 'whole-chain' production, basic developmental needs and future trends broadly remain the same as in the previous iterations of this report (2016 and 2018). Further optimising the performance of new processes and saccharification/fermentation yields, and improving economic and environmental performance (and hence reducing costs) remain critical. Focus has been mainly on ethanol production, but we see large investigations taking place on butanol production, certainly within the EU. The increased scale of projects over time also outside the EU reflects technological progress from intensive R&D. However, better details on cellulosic ethanol production costs may still be higher than recent estimates indicate, both because of high enzyme costs, or high feedstock costs. Further R&D showing reasonable economics and/or a system (pilot plant or demo) running reliably for prolonged periods, with detailed verifiable results will be highly beneficial to all parties involved in this work; it is understood some results can be commercially sensitive, but without clarity on performance, the risk is raised that future investments in R&D are not targeted as efficiently as possible.

6.1.2 Anaerobic digestion

The European AD sector is clearly oriented to improve the digestion of lignocellulosic feedstocks (mainly agricultural residues such as straws) and other complex waste streams (i.e. sludges from wastewater treatment plants), in order to tackle the relevant issues of feedstock availability and sustainability. Technological improvements are however still needed to fully demonstrate the possibility to economically use such feedstocks; processes integration seems currently to be an interesting route to overcome the present barriers.

The need of improving digestate valorisation has been also emerging as a clear target for the sector. Interesting initiatives are in place for nutrients' recovery, by producing market-ready products instead of the current practice of spreading the digestate on the fields. Other projects are currently placing AD plants in the larger framework of biorefinery concepts, and digestate is considered as an interesting substrate for extracting building-blocks for biomaterials synthesis.

For what concerns the biogas downstream, biomethane is the goal of any new investment in AD, but current separation technologies still have to prove their competitiveness. Several technologies already widely used in other industrial sectors, such as Cryogenic gases separation, could benefit from the growing interest in CNG and LNG for transport, but scale down problems are currently limiting their penetration. Support to demo projects, possibly containing relevant integration with other sectors (MSW and waste water managements), could allow making a step forward for the entire sector.

The lack of public awareness, about the potential benefits of AD, is still limiting the technical efforts ongoing in scaling down the technologies; interesting possibilities to enlarge feedstock base, by improving the recovery of waste streams at urban and peri-urban levels, appear not fully exploited. Several projects are promoting actions to fill the gap but a constant effort is needed to obtain positive support to valuable initiatives.

6.2 Thermochemical technologies

6.2.1 BtL and SNG

For the time being, no large-scale gasification plants producing BtL biofuels are in operation. However, a number of opportunities for the improvement of the gasification, syngas cleaning and FT synthesis have been identified in IRENA 2016 as being able to decrease the production costs (up to 15% of current costs) and to result in efficiency gains of the process.

Possible future improvements on which R&D activities may concentrate the efforts include:

- Optimization of the process at smaller scales, developing new concepts which are suitable to smaller size range resulting in lower capital and operational costs.
- Process integration within the whole plant in order to improve the overall energy balance of the plant reducing the need for external energy imports. The integration can be also with industrial sites or district heating networks.
- Development of biomass handling and reliable gasification systems with greater feedstocks tolerance also able to produce a high-quality syngas.
- Development of novel clean-up systems to reduce impurities from syngas and to limit the energy requirements for its upgrading.
- Development of new catalysts that are less susceptible to impurities and have longer lifetimes would help to reduce costs.
- Co-processing of FT products at existing crude oil refinery sites in order to achieve greater economies of scale and efficiencies as well as tailoring the product portfolio according to the market needs.

Specifically for SNG, with the exception of the AMBIGO initiative, the sector is clearly showing a lack of confidence about the possibility to profitably produce SNG via biomass gasification. The cancelling of the EU largest initiative (GoBiGas) can be considered as paradigmatic of the current state of play. Interestingly, a shift in stakeholder attestation can be observed, as the scientific and industrial communities seem currently focusing on methanation as a promising technology for the power to fuel applications.

6.2.2 Fast Pyrolysis

IRENA suggest that there are major opportunities to improve the pyrolysis process through the development of processes able to maximise bio-oil yields, and the use of catalysts able to promote higher selectivity and productivity of desirable products (IRENA, 2016). Areas of investigation to improve catalysts include deactivation, longer lifetime, better stability and cost reduction.

Catalyst improvements are also a major opportunity in the upgrading step. More dedicated research is required to reduce hydrogen consumption during hydro-treatment. Past projects such as the FP7-CASCATBEL as well as on-going project such as 4REFINERY have already published or are investigating several technical developments using catalytic fast pyrolysis and up-grading via refining processes but they need to be scaled up.

The use of tailored-made catalyst that will reduce the hydrogen consumption and ways to produce bio-hydrogen through renewable sources are also under investigation as a way to minimize fossil energy requirement and reduce production costs.

Co-feeding pyrolysis oil in oil refinery units using existing infrastructure and commercial technologies is another promising opportunity investigated by current H2020 projects. This would bring significant cost savings compared to dedicated upgrading units.

According to IRENA, the majority of cost reductions are expected to occur in upgrading, and innovations could ultimately lead to a 10-30% fuel cost reduction.

Another important area of investigation is to produce pyrolysis liquids from cheaper residual resources, while maintaining a product quality meeting the specifications for bio-liquid.

It's worth mentioning that the latest review of BETO's projects (BETO, 2017) evaluated the work on fast pyrolysis as lacking of evidence for significant breakthroughs that would support an extensive commercial application of pyrolysis liquids as an alternative to oil and suggested to deemphasize research on pyrolysis to a sort of extent.

Investigations on other processes combining different routes, such as Thermo-Catalytic Reforming (TCR®) that combines intermediate pyrolysis with post catalytic reforming of the pyrolysis products also attracted funding, but their achievements are not clear at the time of writing the report.

6.2.3 HTL

The HTL pathway, which has been proven in laboratory and/or pilot units, appears as a promising option for the production of bio-crude oil that can be blended with traditional fossil crude and with a view to their being upgraded at existing oil refineries. The challenge of ongoing projects led by Steeper Energy Aps (SEA) industry in Denmark and by Licella Pty Ltd company in Australia is to move the TRL from 5-6 (pilot) to 7-8 (nearly commercial) via testing, scale-up and demonstration. In both cases, R&D actions involve testing various feedstock types to determine the optimal operating parameters for development and demonstration of HTL platform and upgrading reactor configuration. The key objective is to validate current process assumptions, first-hand data on large-scale, outdoor, year-round operation is required. Most recently, Licella appear to be moving closer to this point through the integration of their technology into a paper mill. Better understanding of HTL technology is needed to identify specific challenges and promote cost-effective conversion pathways. Techno-economic analyses will have to be conducted as research and development progresses over the next few years. An interesting development which may be a solution to the relatively limited progress on upgrading of bio-oils are initiatives of NesteOil (Neste Oil-2, 2018) and Repsol (REPSOL, 2016) are now performing tests at scale to co-process HTL with crude oil, but at very low blend levels. Technical barriers are still present but at low blend level (1%) the results appear promising, and some certainty on the specifications of the bio-oil will be helpful. Further work to reduce the loss of carbon in the aqueous (non bio-oil phase) would further help improve overall efficiency.

6.3 Oleochemical technologies

6.3.1 FAME and HVO

For FAME and HVO, work to find more sustainable feedstocks will be necessary especially given the move away from food-based feedstocks for biofuels, and the large increases in HVO production capacity in the EU. More specifically for FAME, heterogeneous catalysts may improve process efficiencies, reduce waste water volumes and improve glycerine purity. Focussing on proving the industrial reliability of such technologies will likely increase the likelihood of industry take-up. Further to develop ethanol as the reaction alcohol (instead of methanol) may be a useful step towards improving the sustainability of the process. However, this may be difficult to progress industrially as methanol is a cheaper alcohol and therefore the first choice of FAME factories. Expanding the uses of the glycerol co-product or improving its valorisation would be beneficial, as there is considerable over supply of this FAME process by-product already.

As already described in previous sections of the report, the use of waste lipidic feedstocks in oleochemical processes, to produce advance drop-in fuels, can be considered as a mature technology. Nevertheless, the sector is facing some relevant challenges, with respect to its environmental sustainability. On this aspect, the possibility to be more flexible with respect to the feedstocks is a key element, currently driving the sector technological development. The possibility to use a wider variety of waste streams (not necessarily only derived from lipid materials) requires, at plant level, the adoption of complex pretreatment sections. This effort is justified by the need to find economic and environmentally viable alternatives to feed the processes.

In parallel to the input flexibility issue, plants are also required to be more and more flexible with respect to the outputs. As the use of biofuels is spreading from road to other transport sectors, namely air and waterborne, the relative shares of diesel, kerosene and naphtha need to be tuned, according to the specific market demand. This trend requires flexibility and high integration among the process steps; this aspect requires further technological investigation. Again, the introduction of pretreatment technologies, able to standardize the feedstock for the process, can be considered as a suitable strategy to meet all these challenges.

Finally, in order to improve the environmental performance of HVO/HEFA production, it is worth noting that securing greater levels of supply of sustainable hydrogen could be considered as a likely imminent field of interest. This is especially pertinent given the trend of increasing production capacities for this technology in the EU.

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List of figures

List of tables

Annexes

Annex 1. Plants identified outside EU

Table A 1. First-of-a-kind fermentation plants outside Europe (TRL 8) (NA= not available) (Padella et al., 2019)

Project owner - project name	Country	Feedstock	Main Product	Output capacity (t/y)	Status	Start-up
Abengoa Bioenergy Biomass of Kansas, LLC - Commercial (sold to Synata Bio Inc. in 2016)	US	Corn stover, wheat straw, switchgrass	Ethanol	75 000	Idle	2014
Aemetis - Aemetis Commercial	US	Biomass syngas	Ethanol	35 000	Planned	2019
Beta Renewables (acquired by Versalis) - Alpha	US	Energy grasses	Ethanol	60 000	On hold	2018
Beta Renewables (acquired by Versalis) - Fujiang Bioproject	China	Wheat straw, corn stover	Ethanol	90 000	On hold	2018
Borregaard Industries AS - ChemCell Ethanol	Norway	Sulfite spent liquor from spruce wood pulping	Ethanol	15 800	Operational	1938
COFCO Zhaodong Co. - COFCO Commercial	China	Lignocellulosic crops	Ethanol	50 000	Planned	2018
DuPont - Commercial facility Iowa (acquired by VERBIO)	US	Corn stover	Ethanol	82 672	Idle	2016
Fiberight LLC - Commercial Plant	US	Organic residues and waste streams	Ethanol	18 000	Under construction	2019
GranBio - Bioflex 1	Brazil	Sugarcane bagasse and straw	Ethanol	65 000	Operational	2014
Henan Tianguan Group - Henan 2	China	Lignocellulosic crops	Ethanol	30 000	Idle	2011
Ineos Bio - Indian River County Facility (acquired by Alliance Bio-Products in 2016)	US	Vegetative waste, waste wood, garden waste	Ethanol	24 000	Idle	NA
Longlive Bio-technology Co. Ltd. – Longlive	China	Corn cob	Ethanol	60 000	Idle	2012
POET-DSM Advanced Biofuels - Project Liberty	US	Agricultural residues	Ethanol	75 000	Operational	2014
Raizen Energia – Brazil	Brazil	Bagasse	Ethanol	36 000	Operational	2015

Table A 2. First-of-a-kind BtL plants outside Europe (TRL 8) (NA = not available)

Project owner and project name	Country	Feedstock	Main Product	Output capacity (t/y)	Status	Start-up
Enerkem Alberta Biofuels LP – Edmonton Waste-to-Biofuels Project	Canada	Post-sorted (after recycling and composting) Municipal Solid Waste	Methanol/Ethanol	30 000	Operational; began methanol production in 2015, and ethanol production in 2019	2014
Velocys	US	forest residues	FT liquids	72 000	Planned	NA
Red Rock Biofuels - Commercial	US	Forestry residues	FT liquids	44 000	Under construction	2020
Fulkrum (Sierra Biofuels) - Sierra	US	Pre-processed Municipal Solid Waste	FT liquids	30 000	Under construction	2020

Table A 3. First-of-a-kind fast-pyrolysis plants outside Europe (TRL 8) (NA= not available) (IEA Bionergy Task 39 Database))

Project owner - project name	Location and country	Feedstock	Main Product	Output capacity (t/y)	Status	Start-up
Ensyn – Cote Nord Project	Canada	Forest residues	Transportation fuel	36 000	Operational	2018
Biozin - Biozin biocrude	Norway	Forestry residues and by-products from saw mill industry	Bio-oil	100 000	Planned	2022

Annex 2. Information on EU and SET-Plan flagship projects

Table A 4. General information on H2020 projects classified by sub-technology

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
RIA - Research and Innovation action	Fermentation	Ambition	731263	01/12/2016	30/11/2019	2,494,986	2,494,986	STIFTELSEN SINTEF	Norway	10
RIA - Research and Innovation action	Fermentation	BAB-ET-REAL5	654365	01/02/2016	31/01/2020	5,573,644	5,995,199	INSTITUT NATIONAL POLYTECHNIQUE DE TOULOUSE	France	16
RIA - Research and Innovation action	Fermentation	BECOOL	744821	01/06/2017	31/05/2021	4,999,955	4,999,955	ALMA MATER STUDIORUM - UNIVERSITA DI BOLOGNA	Italy	14
RIA - Research and Innovation action	Fermentation	BioRen	818310	01/11/2018	31/10/2022	4,971,314	5,084,658	D.C. CORPORATE FINANCE	Belgium	10
BBI-IA-FLAG - Bio-based Industries Innovation action - Flagship	Fermentation	BIOSKOH	709557	01/06/2016	31/05/2022	21,568,194	30,122,314	ENERGOCHEMICA TRADING AS	Slovakia	12
RIA - Research and Innovation action	Fermentation	ButaNexT	640462	01/05/2015	30/04/2018	4,599,414	4,599,414	Green Biologics Ltd.	United Kingdom	10
ERC-ADG - Advanced Grant	Fermentation	ELOXY	694633	01/09/2016	31/08/2021	2,498,150	2,498,150	TECHNISCHE UNIVERSITEIT DELFT	Netherlands	1
RIA - Research and Innovation action	Fermentation	FALCON	720918	01/01/2017	31/12/2020	6,148,784	6,555,884	KONINKLIJKE NEDERLANDSE AKADEMIE VAN WETENSCHAPPEN - KNAW	Netherlands	9
BBI-IA-FLAG - Bio-based Industries	Fermentation	LIGNOFLAG	709606	01/06/2017	31/05/2022	24,738,840	34,969,215	Clariant Produkte (Deutschland) GmbH	Germany	8

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
Innovation action - Flagship										
IA - Innovation action	Fermentation	NewLiEP	869879	01/08/2019	31/07/2021	2,878,750	4,112,500	TERRANOL A/S	Denmark	3
IA - Innovation action	Fermentation	REWOFUEL	792104	01/06/2018	31/05/2021	13,856,302	19,791,557	GLOBAL BIOENERGIES	France	11
IA - Innovation action	Fermentation	Torero	745810	01/05/2017	30/04/2020	11,472,916	15,849,490	ARCELORMITTAL BELGIUM NV	Belgium	6
BBI-RIA - Bio-based Industries Research and Innovation action	Fermentation	US4GREENCHEM	669055	01/07/2015	30/06/2019	3,457,603	3,803,925	VEREIN ZUR FORDERUNG DES TECHNOLOGIETRANSFERS AN DER HOCHSCHULE BREMERHAVEN EV	Germany	10
RIA - Research and Innovation action	Fermentation	WASTE2FUELS	654623	01/01/2016	31/12/2018	5,989,743	5,989,744	IRIS TECHNOLOGY SOLUTIONS, SOCIEDAD LIMITADA	Spain	21
SME-2 - SME instrument phase 2	AD	ADD-ON	666427	01/03/2015	31/10/2019	1,414,754	2,021,078	DUCTOR OY	Finland	1
CSA - Coordination and support action	AD	Bin2Grid	646560	01/01/2015	31/12/2017	709,468	709,469	ZAGREBACKI HOLDING DOO	Croatia	8
CSA - Coordination and support action	AD	BiogasAction	691755	01/01/2016	31/12/2018	1,999,885	1,999,885	ENERGY CONSULTING NETWORK APS	Denmark	13
SME-2 - SME instrument phase 2	AD	BIOGASTIGER	783727	01/11/2017	31/10/2019	2,130,363	3,043,375	FICKERT & WINTERLING MASCHINENBAU GMBH	Germany	2

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
CSA - Coordination and support action	AD	BIOSURF	646533	01/01/2015	31/12/2017	1,872,912	1,872,912	ISTITUTO DI STUDI PER L'INTEGRAZIONE DEI SISTEMI (I.S.I.S) - SOCIETA'COOPERATIVA	Italy	12
BBI-IA-DEMO - Bio-based Industries Innovation action - Demonstration	AD	DEMETER	720714	01/08/2016	31/01/2020	4,629,586	6,539,558	GENENCOR INTERNATIONAL BV	Netherlands	7
SME-2 - SME instrument phase 2	AD	DEPURGAN	673771	01/09/2015	30/09/2017	1,890,110	2,702,033	EUROGAN SL	Spain	1
CSA - Coordination and support action	AD	DiBiCoo	857804	01/10/2019	30/06/2022	2,998,181	2,998,181	DEUTSCHE GESELLSCHAFT FUR INTERNATIONALE ZUSAMMENARBEIT (GIZ) GMBH	Germany	13
SME-2 - SME instrument phase 2	AD	HOMEBIOGAS	777770	01/08/2017	31/01/2020	1,604,750	2,292,500	HOMEBIOGAS LTD	Israel	1
CSA - Coordination and support action	AD	ISAAC	691875	01/01/2016	30/06/2018	1,480,535	1,480,535	AZZERO CO2 SRL	Italy	5
CSA - Coordination and support action	AD	ISABEL	691752	01/01/2016	31/12/2018	1,897,438	1,897,438	Q-PLAN INTERNATIONAL ADVISORS PC	Greece	8
SME-2 - SME instrument phase 2	AD	Lt-AD	718212	01/06/2016	31/05/2018	1,693,171	2,418,815	NVP ENERGY LIMITED	Ireland	3
SME-2 - SME instrument phase 2	AD	MUBIC	778065	01/08/2017	31/01/2020	2,499,999	5,466,533	ADVANCED SUBSTRATE TECHNOLOGIES AS	Denmark	2

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
IA - Innovation action	AD	NOMAD	863000	01/10/2019	30/09/2022	4,250,477	5,499,857	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	Greece	15
CSA - Coordination and support action	AD	Record Biomap	691911	01/04/2016	30/09/2018	499,922	499,922	DBFZ DEUTSCHES BIOMASSEFORSCHUNGSZENTRUM GEMEINNUETZIGE GMBH	Germany	4
CSA - Coordination and support action	AD	REGATRACE	857796	01/06/2019	31/05/2022	3,000,485	3,000,488	ISTITUTO DI STUDI PER L'INTEGRAZIONE DEI SISTEMI (I.S.I.S) - SOCIETA'COOPERATIVA	Italy	15
IA - Innovation action	AD	SYSTEMIC	730400	01/06/2017	31/05/2021	7,859,829	9,723,586	STICHTING WAGENINGEN RESEARCH	Netherlands	15
RIA - Research and Innovation action	BTL	CLARA	817841	01/11/2018	31/10/2022	4,993,805	4,993,805	TECHNISCHE UNIVERSITAT DARMSTADT	Germany	13
RIA - Research and Innovation action	BTL	COMSYN	727476	01/05/2017	30/04/2021	5,096,660	5,096,660	Teknologian tutkimuskeskus VTT Oy	Finland	7
RIA - Research and Innovation action	BTL	CONVERGE	818135	01/11/2018	30/04/2022	5,087,031	5,087,031	POLITECNICO DI MILANO	Italy	10
RIA - Research and Innovation action	BTL	FLEDGED	727600	01/11/2016	31/10/2020	5,306,455	5,569,330	POLITECNICO DI MILANO	Italy	11
RIA - Research and Innovation action	BTL	FLEXCHX	763919	01/03/2018	28/02/2021	4,489,545	4,489,545	Teknologian tutkimuskeskus VTT Oy	Finland	10
RIA - Research and Innovation action	BTL / HTL	Heat-To-Fuel	764675	01/09/2017	31/08/2021	5,896,988	5,896,988	GUSSING ENERGY TECHNOLOGIES GMBH	Austria	14

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
MSCA-IF-GF - Global Fellowships	BTL	MECHANISM	703060	19/04/2017	18/04/2020	253,955	253,955	UNIVERSITY OF CYPRUS	Cyprus	2
RIA - Research and Innovation action	BTL	Pulp and Fuel	818011	01/10/2018	30/09/2022	4,954,341	4,954,341	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	France	10
RIA - Research and Innovation action	BTL	REDIFUEL	817612	01/10/2018	30/09/2021	4,999,188	4,999,188	FEV EUROPE GMBH	Germany	12
RIA - Research and Innovation action	Pyrolysis / HTL	4REFINERY	727531	01/05/2017	30/04/2021	5,965,474	5,965,474	SINTEF AS	Norway	9
RIA - Research and Innovation action	Pyrolysis	BioMates	727463	01/10/2016	30/11/2021	5,923,316	5,923,316	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	Greece	9
IA - Innovation action	Pyrolysis / Other	SSOP	760277	01/05/2017	31/10/2019	1,979,584	2,827,978	RIMON CONSULTING & MANAGEMENT SERVICES LTD	Israel	4
IA - Innovation action	Pyrolysis / TCR	TO-SYN-FUEL	745749	01/05/2017	30/04/2021	12,250,528	14,511,923	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	Germany	12
RIA - Research and Innovation action	Pyrolysis / HTL	WASTE2ROAD	818120	01/10/2018	30/09/2022	4,996,155	4,996,155	SINTEF AS	Norway	11
RIA - Research and Innovation action	HTL / Pyrolysis	ABC-SALT	764089	01/04/2018	31/03/2022	3,998,026	3,998,026	RIJKSUNIVERSITEIT GRONINGEN	Netherlands	9
SME-2 - SME instrument phase 2	HTL	Hydrofaction	666712	01/04/2015	31/03/2017	1,841,816	2,631,166	STEEPER ENERGY APS	Denmark	1

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
RIA - Research and Innovation action	HTL	HyFlexFuel	764734	01/10/2017	30/09/2021	5,038,344	5,038,344	BAUHAUS LUFTFAHRT EV	Germany	10
RIA - Research and Innovation action	HTL	NextGenRoad Fuels	818413	01/11/2018	31/10/2022	5,074,876	5,074,876	AALBORG UNIVERSITET	Denmark	11
ERC-STG - Starting Grant	HTL	REBOOT	849841	01/01/2020	31/12/2024	1,494,622	1,494,622	AARHUS UNIVERSITET	Denmark	1
IA - Innovation action	FAME_HVO_HEFA	BIO4A	789562	01/05/2018	30/04/2022	10,002,520	16,860,911	CONSORZIO PER LA RICERCA E LA DIMOSTRAZIONE SULLE ENERGIE RINNOVABILI	Italy	8
IA - Innovation action	FAME_HVO_HEFA	BioDie2020	737802	01/12/2016	30/11/2019	2,119,087	2,825,586	ARGENT ENERGY (UK) LIMITED	United Kingdom	6
IA - Innovation action	FAME_HVO_HEFA + TCR	FlexJET	792216	01/04/2018	31/03/2022	9,999,733	15,033,205	THE UNIVERSITY OF BIRMINGHAM	UK	13
SME-2 - SME instrument phase 2	FAME_HVO_HEFA	SOLARIS	778030	01/08/2017	31/08/2019	1,115,156	1,593,079	IDROEDIL SRL	Italy	1
MSCA-IF-GF - Global Fellowships	Algae	BioMIC-FUEL	702911	01/01/2017	31/12/2019	251,858	251,858	THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE	United Kingdom	2
SME-2 - SME instrument phase 2	Algae	ECO-LOGIC GREEN FARM	683515	01/08/2015	31/01/2017	2,488,150	3,554,500	SOCIETA' AGRICOLA SERENISSIMA S.S.	Italy	1
SME-2 - SME instrument phase 2	Algae	INTERCOME	733487	01/12/2016	30/11/2018	1,698,506	2,426,438	ALGAENERGY SA	Spain	1
RIA - Research and Innovation action	Algae	MacroFuels	654010	01/01/2016	31/12/2019	5,999,893	5,999,893	TEKNOLOGISK INSTITUT	Denmark	12

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
MSCA-ITN-ETN - European Training Networks	Algae	SE2B	675006	01/03/2016	29/02/2020	3,866,945	3,866,945	JOHANN WOLFGANG GOETHE-UNIVERSITATFRANKFURT AM MAIN	Germany	12
ERC-STG - Starting Grant	Algae	SOLENALGAE	679814	01/03/2016	28/02/2021	1,441,875	1,441,875	UNIVERSITA DEGLI STUDI DI VERONA	Italy	2
RIA - Research and Innovation action	Biorefineries	AgroCycle	690142	01/06/2016	31/05/2019	6,960,294	7,650,050	UNIVERSITY COLLEGE DUBLIN, NATIONAL UNIVERSITY OF IRELAND, DUBLIN	Ireland	26
SME-2 - SME instrument phase 2	Biorefineries / Fermentation	APEX	666346	01/04/2015	31/03/2017	1,541,575	2,202,250	METGEN OY	Finland	1
IA - Innovation action	Biorefineries	AQUACOMBINE	862834	01/10/2019	30/09/2023	9,789,884	11,072,052	AALBORG UNIVERSITET	Denmark	17
CSA - Coordination and support action	Biorefineries	BIOPLAT-EU	818083	01/11/2018	31/10/2021	2,490,408	2,490,408	WIRTSCHAFT UND INFRASTRUKTUR GMBH & CO PLANUNGS KG	Germany	12
IA - Innovation action	Biorefineries / AD	DECISIVE	689229	01/09/2016	28/02/2021	7,755,102	8,708,643	INSTITUT NATIONAL DE RECHERCHE EN SCIENCES ET TECHNOLOGIES POUR L'ENVIRONNEMENT ET L'AGRICULTURE	France	14
BBI-RIA - Bio-based Industries Research and Innovation action	Biorefineries	EXCornsEED	792054	01/06/2018	30/11/2021	4,259,297	4,483,469	UNIVERSITA DEGLI STUDI DI ROMA LA SAPIENZA	Italy	14
BBI-IA-DEMO - Bio-based Industries Innovation	Biorefineries	GRACE	745012	01/06/2017	31/05/2022	12,324,633	15,000,851	UNIVERSITAET HOHENHEIM	Germany	23

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
action - Demonstration										
IA - Innovation action	Biorefineries / AD	INCOVER	689242	01/06/2016	31/07/2019	7,209,032	8,432,456	ASOCIACION DE INVESTIGACION METALURGICA DEL NOROESTE	Spain	18
ERC-COG - Consolidator Grant	Biorefineries	LIGNINFIRST	725762	01/03/2017	28/02/2022	1,999,756	1,999,756	IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	United Kingdom	1
BBI-IA-DEMO - Bio-based Industries Innovation action - Demonstration	Biorefineries	LigniOx	745246	01/05/2017	30/04/2021	4,338,375	5,768,734	Teknologian tutkimuskeskus VTT Oy	Finland	12
RIA - Research and Innovation action	Biorefineries	MAGIC	727698	01/07/2017	30/06/2021	5,999,988	5,999,988	CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING FONDATION	Greece	26
IA - Innovation action	Biorefineries	MOBILE FLIP	637020	01/01/2015	31/12/2018	8,606,175	9,698,843	Teknologian tutkimuskeskus VTT Oy	Finland	14
RIA - Research and Innovation action	Biorefineries / AD	NoAW	688338	01/10/2016	30/09/2020	6,887,570	7,816,233	INSTITUT NATIONAL DE LA RECHERCHE AGRONOMIQUE	France	33
BBI-RIA - Bio-based Industries Research and Innovation action	Biorefineries / Fermentation	PERCAL	745828	01/07/2017	30/06/2020	2,518,518	3,394,181	INDUSTRIAS MECANICAS ALCUDIA SA	Spain	13
BBI-IA-DEMO - Bio-based Industries Innovation	Biorefineries	URBIOFIN	745785	01/06/2017	31/12/2021	10,946,366	14,606,669	INDUSTRIAS MECANICAS ALCUDIA SA	Spain	17

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
action - Demonstration										
BBI-RIA - Bio-based Industries Research and Innovation action	Biorefineries / Fermentation	Zelcor	720303	01/10/2016	30/09/2020	5,256,993	6,728,695	INSTITUT NATIONAL DE LA RECHERCHE AGRONOMIQUE	France	17
MSCA-ITN-EJD - European Joint Doctorates	Overarching / Cross Cutting / Support Actions	ABWET	643071	01/01/2015	31/12/2018	3,918,951	3,918,951	UNIVERSITA DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE	Italy	5
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	ADVANCEFUEL	764799	01/09/2017	31/08/2020	2,628,246	2,628,246	Fachagentur Nachwachsende Rohstoffe e.V.	Germany	9
ERA-NET-Cofund - ERA-NET Cofund	Overarching / Cross Cutting / Support Actions	BESTF3	691637	01/01/2016	31/12/2020	2,137,532	6,477,369	DEPARTMENT FOR BUSINESS ENERGY AND INDUSTRIAL STRATEGY	United Kingdom	10
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	BIOFIT	817999	01/10/2018	30/09/2021	2,626,238	2,626,238	B.T.G. BIOMASS TECHNOLOGY GROUP BV	Netherlands	14
MSCA-RISE - Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE)	Overarching / Cross Cutting / Support Actions	BIOMASS-CCU	823745	01/01/2019	31/12/2022	846,400	1,168,400	THE QUEEN'S UNIVERSITY OF BELFAST	UK	8
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	BioReg	727958	01/01/2017	31/12/2019	996,056	996,056	CABINET D'ETUDES SUR LES DECHETS ET L'ENERGIE	France	9

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	BioRES	645994	01/01/2015	30/06/2017	1,865,411	1,865,411	DEUTSCHE GESELLSCHAFT FUR INTERNATIONALE ZUSAMMENARBEIT (GIZ) GMBH	Germany	10
RIA - Research and Innovation action	Overarching / Cross Cutting / Support Actions	BRISK II	731101	01/05/2017	30/04/2022	9,968,144	9,977,271	KUNGLIGA TEKNISKA HOEGSKOLAN	Sweden	17
IA - Innovation action	Overarching / Cross Cutting / Support Actions	COLHD	769974	01/11/2017	31/10/2020	8,984,735	12,430,314	IDIADA AUTOMOTIVE TECHNOLOGY SA	Spain	16
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	ETIP Bioenergy-SABS	727509	01/09/2016	31/08/2018	599,105	599,105	Fachagentur Nachwachsende Rohstoffe e.V.	Germany	4
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	FORBIO	691846	01/01/2016	31/12/2018	1,941,581	1,941,581	WIRTSCHAFT UND INFRASTRUKTUR GMBH & CO PLANUNGS KG	Germany	12
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	GasFermTEC	810755	01/09/2018	31/08/2023	2,496,875	2,496,875	TARTU ULIKOOL	Estonia	1
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	greenGain	646443	01/01/2015	31/12/2017	1,829,391	1,829,391	Fachagentur Nachwachsende Rohstoffe e.V	Germany	8
RIA - Research and Innovation action	Overarching / Cross Cutting / Support Actions	JETSCREEN	723525	01/06/2017	31/05/2020	7,469,355	7,469,355	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Germany	15
CSA - Coordination	Overarching / Cross Cutting	MUSIC	857806	01/09/2019	31/08/2022	2,999,871	2,999,871	B.T.G. BIOMASS TECHNOLOGY GROUP BV	Netherlands	16

Funding scheme	Type	Project Acronym	Project ID	Start Date	End Date	EU Contribution (EUR)	Total cost (EUR)	Coordinator	Country	Number of Participants
and support action	/ Support Actions									
MSCA-RISE - Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE)	Overarching / Cross Cutting / Support Actions	Phoenix	690925	01/12/2015	30/11/2019	1,377,000	1,377,000	EUROPEAN SUSTAINABLE ENERGY INNOVATION ALLIANCE - ESEIA, VEREIN FUR FORDERUNG DER EUROPAIESCHEN INNOVATION FUR ERNEUERBARE ENERGIEN	Austria	14
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	SECURECHAIN	646457	01/04/2015	31/03/2018	1,809,586	1,809,586	B.T.G. BIOMASS TECHNOLOGY GROUP BV	Netherlands	11
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	SEEMLA	691874	01/01/2016	31/12/2018	1,629,884	1,629,884	Fachagentur Nachwachsende Rohstoffe e.V.	Germany	8
ERC-COG - Consolidator Grant	Overarching / Cross Cutting / Support Actions	SIZE	647224	01/09/2015	31/08/2020	1,670,406	1,670,406	STICHTING KATHOLIEKE UNIVERSITEIT	Netherlands	1
CSA - Coordination and support action	Overarching / Cross Cutting / Support Actions	uP_running	691748	01/04/2016	30/06/2019	1,992,920	1,992,920	FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS	Spain	12

Table A 5. General information on SET-Plan flagship projects classified by sub-technology (NA = Not Available)

Name project/plant	Type	Country	Coordinator/main partner	Timeline	Technology providers	Other partners	Budget (EUR million)
Austrocel Hallein GmbH	Fermentation	Austria	AustroCel Hallein GmbH	2019 - 2020+	NA	NA	40
DELFT AB	Fermentation	Netherlands	DELFT AB	2018 - 2022	DSM	NA	NA
Eni Refinery	Fermentation	Italy	Eni	2018 - 2019	Eni, Saccharification technology provider to be determined	NA	4
Futurol	Fermentation	France	PROCETHOL 2G	NA	LESAFFRE, IFP Energies Nouvelles, ARD Innovation in Green, INRA	VIVESCIA, Tereos, Total, Office National des Forets, Unigrains, CA Nord Est, CBG	76.4 (including 29.9 national funding)
Oscyme	Fermentation	Austria	AEE Institute for Sustainable Technologies	2017+	NA	ACIB, AUT; UNEW, UK; EU plant manufacturer	NA
BioMethER	AD	Italy	LEAP S.C.A R.L.	2013 - 2018 (delayed)	SOL	ASTER S.cons.p.A., Regione Emilia-Romagna, CRPA Lab, IREN Rinnovabili, IRETI, Iren S.p.A, HERAmbiente, SOL Group	3.4
VERBIO	AD	Germany	Verbio	2014 - 2019	Verbio	NA	Confidential (22 from NER300)
PSI's catalytic fluidized bed technology	AD	Switzerland	PSI	2016 - 2017	PSI, Energie360°	Forschungs-, Entwicklungs- und Förderungsfonds der schweizerischen Gasindustrie (FOGA)	1
BioTFuel	BtL	France	Total	2019 + (for commercial deployment)	Axens, IFP Energies Nouvelles, French Alternative Energies and Atomic Energy Commission (CEA),		178.1 (including 33.2 national funding)

Name project/plant	Type	Country	Coordinator/main partner	Timeline	Technology providers	Other partners	Budget (EUR million)
					Sofiproteol, ThyssenKrupp Uhde, Total		
BTL 2030	BtL	Finland	VTT	First phase 2016 - 2018	NA	Fortum Oyj, Gasum Oy, Helen Oy, Kumera Corporation, Gasification Technologies, Oy, Oy Brynolf Grönmark Ab, ÅF-Consult Oy, Oy Woikoski Ab, Dasos Capital Oy, Kokkolanseudun Kehitys Oy, MOL Group	2.7 (first phase)
Güssing Gasifier	BtL	Austria	Bioenergy 2020+	2018 - 2023	Bioenergy 2020+	Interested in cooperation: Wien Energie, MA48, TU Wien	NA
Winddiesel	BtL	Austria	GET	Not yet defined	REPOTEC, TU-Vienna, GET	ECE, Energie Burgenland, Bilfinger	150
AMBIGO	SNG	Netherlands	ECN	2018 - 2020	Dahlman RT, Zeton, ESME, Frames, ECN	ENGIE, GasUnie	25
bioCRACK / bioBOOST	Pyrolysis	Austria	BDI (Bioenergy International AG)	2007 - ongoing	BDI	Graz University of Technology, CEET; OMV	12 (until now)
bioliq project	Pyrolysis	Germany	KIT	2005 - ongoing	Air Liquide, Chemieanlagen-bau Chemnitz and others	KIT PhD network, national and international R&D partners	NA
EMPYRO	Pyrolysis	Netherlands	BTG	NA	BTG	Friesland Campina	NA
Integration to refinery co-feed	Pyrolysis / HTL	Finland	VTT	Ongoing	NA	NA	5

Name project/plant	Type	Country	Coordinator/main partner	Timeline	Technology providers	Other partners	Budget (EUR million)
Neste oil Porvoo refinery	Pyrolysis / HTL	Finland	Neste Oil	Ongoing	NA	NA	NA
RenFuel	Pyrolysis / Other	Sweden	Renfuel	First phase 2015 - 2018	Valmet, Poyry, Buchi, GEA	Nordic Paper, Rottneros, Valmet, Preem, RiSe, MoRe, Stockholm University, Uppsala University, Sveriges Lantbruksuniversitet	14
WASTE TO FUEL Gela Refinery	HTL	Italy	Eni	2017 - 2018	Eni	NA	2.5
Gela Green Refinery	FAME_HVO_HEFA	Italy	ENI	2016 - 2018	Eni-UOP (Ecofining™)	NA	240

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