European Commission

LOW CARBON ENERGY OBSERVATORY

HEAT AND POWER FROM BIOMASS

Technology development report

Joint Research Centre

EUR 29910 EN

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EU Science Hub

https://ec.europa.eu/jrc

JRC118318

EUR 29910 EN

PDF	ISBN 978-92-76-12432-0	ISSN 2600-0466 ISSN 1831-9424 (online collection)	doi:10.2760/919071
Print	ISBN 978-92-76-12433-7	ISSN 2600-0458 ISSN 1018-5593 (print collection)	doi:10.2760/19308

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: N. Scarlat, F. Fahl, Heat and Power from Biomass Technology Development Report 2018, EUR 29910 EN, European Commission, Luxemburg, 2019, ISBN 978-92-76-12432-0, doi:10.2760/919071, JRC118318.

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Foreword on 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 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.

Acknowledgements

The authors would like to thank JRC colleagues who contributed to this report: The energy modelling work has been performed by the JRC-EU-TIMES team: Wouter Nijs, Pablo Ruiz Castello and Ioannis Tsiropoulos.

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1 Introduction

This Technology Development Report for Heat and Power from Biomass is an update to the version produced in 2016. Since then, the European Parliament, the Council and the European Commission have agreed on 32% targets for the renewable energy in the final energy consumption and 14% renewable energy in transport 2030, as well as on a sub-target of 3.5 % for advanced biofuels. The Commission has proposed reinforced EU sustainability criteria for bioenergy to cover biofuels but also biomass and biogas for heat and power that include GreenHouse Gas (GHG) savings compared to fossil fuels, the avoidance of deforestation or degradation of habitats or loss of biodiversity. The sustainability criteria also include requirements to ensure high conversion efficiency of biomass into energy, the efficient use of limited resources and to avoid negative impacts on other (competitive) uses. The EU sustainability criteria are extended to cover solid biomass and biogas used in large heat and power plants (above 20 MW fuel capacity) and delivers at least 80% fewer GHG emission compared to fossil fuels by 2021 and 85% less by 2026. Large-scale new biomass electricity plants (above 20 MW) will need to use high efficient Combined Heat and Power (CHP) technology, reaching efficiencies above 80% (this criterion does not apply in case of risks to the security of electricity supply).

The global primary energy supply from biomass has reached about 60 EJ in 2015, representing a share of the total global primary energy consumption of 10 % and a share in the final energy consumption of 14 %. The traditional use of biomass, primarily for cooking and heating, has an important contribution, accounting for about 8.9% of the global final energy consumption (REN 21 2016). Bioenergy is likely to keep its major role in the European Union as renewable energy source in the energy mix until 2020 with a share above 60 % of renewable energy and a share in the gross final energy consumption of about 12 % in 2020 (Scarlat et al. 2018). Biomass used worldwide for energy consists mainly in solid biomass and includes fuel wood, charcoal, crop residues, organic Municipal Solid Waste (MSW), wood pellets, and wood chips in modern, small and large-scale facilities. Traditional use of biomass relies mainly in fuelwood, charcoal, manure and agricultural residues burned in open fires, stoves and ovens for cooking and heating applications (Scarlat et al. 2018).

Biomass electricity capacity reached an installed capacity in 2015 of about 106 GW at worldwide level and 30 GW in operation in the EU, world leader for bio-power generation and capacity. The global biomass electricity power generation also reached 474 GWh in 2015, with a large share of biomass electricity being produced in the EU (178 TWh). Global biogas production increased from 0.28 EJ in 2000 to 1.28 EJ in 2014, with a global volume of 35 billion m^3 methane equivalent, of which 18 billion m^3 methane equivalent being produced in the European Union (Eurostat 2018, IEA 2016). The global installed biogas capacity reached in 15 GW in 2015, with more than 10 GW in the European Union only. Europe is also leading in electricity production from biogas, with 58 TWh electricity generated only in the European Union, out of the global electricity production of 80 TWh in 2014 (REN21 2016, Eurostat 2018).

In the heating sector more than two-thirds of the use of renewable energy worldwide was traditional biomass (firewood, charcoal, manure and crop residues). Biomass use for heat represented 45 EJ worldwide in 2014, having a share of 75 % of total global biomass demand, of which about 70% (31.5 EJ) was produced from traditional biomass, mainly in rural areas in Asia (19.1 EJ) and Africa (11.6 EJ). Biomass accounted for over 90% of modern renewable heat generation in 2015 (REN21 2016, Eurostat 2018). Most bio-heat is derived from solid biomass, but biogas is becoming a more important source for heat production, providing about 4 % of the bioheat worldwide in 2015. Biogas is used primarily in electricity and CHP plants, with small amounts used in heat-only plants. About 50% of total biogas consumption in Europe (more than 330 PJ) was used for heat production. Small biogas amounts upgraded to biomethane were used in the transport sector; limited volumes of biogas upgraded to natural gas quality are now being injected into the natural gas grids. A number of large-scale plants that run on biogas are also operating across Asia and Africa. Biogas is also produced in a growing number of small, domestic-scale digesters, mainly in developing countries - including China, India, Nepal, and Rwanda - and is used as a cooking fuel (REN21 2016).

Bioenergy production is based on a large extent on biomass combustion (including biomass co-firing with coal, waste incineration in waste to energy plants) and biogas production in Anaerobic Digestion (AD) plants (of organic materials and wastewater treatment), and from landfill gas recovery. The biomass combustion process, based on steam turbine cycle, produce heat, electricity or CHP using a large range of feedstock from wood chips, wood pellets, agricultural and forestry waste, etc. Biomass combustion and biogas production for electricity generation are economically viable if adequate support is provided (feed in tariffs, premiums, investment grants, etc.) or low-cost or no-cost biomass feedstock is available (such as waste and residues from agriculture forestry, households or industry). The production of heat by direct combustion of biomass is often cost-competitive with fossil fuel alternatives residential and industrial applications.

Biomass heating is applied at large scale in households in stoves, using wood logs or wood pellets, or in small boilers using wood pellets. In the industry sector, heating is produced in boilers using wood chips or wood pellets or in district heating, especially in several MS where the district heating networks are developed (Austria, Denmark, Finland, Sweden, etc.). Other biomass conversion technologies are still at pilot or demonstration stage and require further technological improvements and demonstration of technical and economic performances at large, commercial scale. Several demonstration plants have been built and technologies are being tested at pilot, or semi-commercial scale based on pyrolysis, gasification, torrefaction or hydrothermal processing (liquefaction). Some biorefinery plants at demo scale have been built, taking advantage of existing infrastructure and expertise of pulp and paper production and certain processes are closer to commercial application. Algae are being increasingly considered a potentially interesting feedstock for a number of applications to produce biochemicals, biomaterials, fuels and energy through a number of adequate processing including AD, pyrolysis, hydrothermal liquefaction, and gasification.

The natural biomass resources are limited. Biomass availability, competition between the alternative use of biomass, as well as the environmental implications are major concerns for bioenergy deployment. Bioenergy production, however, brings significant opportunities to deliver a number of social, environmental and economic benefits in addition to the climate and energy goals, in relation to food production, water, ecosystems, health and welfare. Most studies show that available biomass resources have the potential to expand from current 60 EJ to 145 EJ worldwide by 2060, as required by the IEA 2DS (2 Degree Scenario) and B2DS (Beyond 2 Degree Scenario) (IEA 2017) and between 10-12.6 EJ in the European Union in 2050. Furthermore, biomass can be used not only for electricity production, but also for heat and as transport fuels and lately for bio-based materials or for bio-chemicals. Biomass mobilisation, including small flows, waste and residues from agriculture and forestry, is critical for further increase in bioenergy production.

1.1 Methodology

This report presents an assessment of the state of the art of key technologies for heat and power from biomass. The main goal is to identify their development status, ongoing research and development (R&D) efforts, and perspectives for improvement and research needs. It also aims to define the areas for further R&D that will allow achieving high deployment rates for bioenergy. The various biomass technologies were analysed, based on their technological advancement and their potential to provide a significant contribution to decarbonisation of the European energy system in the short-and medium- to long-term period.

The analysis focused on the main technologies that are currently used for heat and power production or have good prospects for entering soon on the market, including biomass combustion, AD, as well as torrefaction, pyrolysis, hydrothermal processing and gasification. Biorefineries, integrating a number of biomass technologies in complex systems, producing energy, biomaterials and biochemicals, were also included in this analysis. This report also considers the use of aquatic biomass (algae), as novel feedstocks for bioenergy production that show high potential and great perspectives for future development.

These various technologies, although in different stages of development, have undergone significant improvements and technical advances in the last years. However, most of them face technical and non-technical challenges and barriers that impede on their large scale commercial application that will be discussed in the report. Some technologies still require research support to improve their technical, economic and environmental performances to achieve commercial operation.

In order to address the different tasks, set out for this report, detailed analysis of the biomass technologies has been carried out, involving in-depth literature reviews, employment of technology specific database, collection of techno-economic information and analysis of the information to provide a comprehensive assessment of the bioenergy sector. The technology assessment section depicts the state of the art of bioenergy technologies, including the analysis of the European R&D framework research programmes and international research activities. The report provides an analysis of the topics, objectives and results of past and on-going EU projects and how these compare to the state of the art, as well as to the international trends.

Technology projections were based on the JRC-EU-TIMES model to estimate the future contribution of bioenergy production in the European energy sector (Simoes et al 2013).

Bioenergy technologies are a cluster of many individual technologies contributing to heat and power applications with different levels of development. The assessment of the bioenergy technologies has been made on the basis of their Technology Readiness Level (TRL), as well as on the guiding principles established for renewable energy technologies in the DG RTD report (De Rose et al., 2017). Technology Readiness Level (TRL) is a tool widely used for a technology maturity assessment and allows also a consistent comparison of maturity between different types of technologies (Table 1).

It should be noted that most of the H2020 and SET-Plan flagship projects under analysis are on-going projects and therefore the assessment of their current impact was hindered by no availability of final project results and deliverables. The available information on projects has been collected from CORDIS website and other sources.

Table 1. Technology Readiness Level scale used by Horizon2020 for the eligibility assessment of projects

TRL	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment
TRL 6	Technology demonstrated in relevant environment
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment

1.2 Data sources

The main data sources used to assess the state of the art of the technologies and to identify the relevant European R&D projects came from several sources of information from literature and R&D project data.

The relevant projects and the overall funding efforts under the EU R&D framework programmes were identified from CORDIS, the public repository and portal to disseminate information on all EU-funded research projects and their results, IEE project database, other databases and project websites. The main focus has been on the assessment of project results from EU-funded FP7

(2007-2013), IEE (2003-2013), and H2020 (2014-2020) RTD programmes, as well as in the NER300 (2014-2018) and selected international projects.

For each selected technology relevant projects have been identified by searching for a combination of keywords from CORDIS and other databases: bioenergy, biomass conversion, heat and power, biogas, biomethane, combustion, torrefaction, pyrolysis, gasification, syngas, thermochemical conversion, hydrothermal processing, biorefinery, algae. The relevant identified projects have been analysed in detail, in terms of objectives and main achievements in order to define their impact on the development of the technology.

In addition to projects funded under the Horizon 2020 (H2020), the present study screened NER 300, Knowledge and Innovation Community (KIC)-Innoenergy, InnovFin and the European Fund for Strategic Investments (EFSI) schemes for relevant projects. Moreover, national research councils have been analysed. In particular R&D projects supported by national research organisations of countries with a strong tradition in bioenergy were identified.

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" have been included in the analysis (SET Plan 2018). 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".

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

The selection included the most relevant projects in terms of the scope, conversion technology involved and the potential contribution to the advancement in technology. The projects related mainly to heat and power from biomass and to a lower extent, to biofuels for transport, which they are treated in a separate LCEO report, as the authors acknowledge the synergies between biomass conversion technologies that could be used for heat and power generation and for the production of energy carriers and liquid biofuels that could be used in transport. The analysis focussed on the project reports, main deliverables and project summaries, depending on the availability of data. Some of the identified projects have been already finished, while other projects are in-progress and for the later the expected developments were assessed. Significant uncertainty has to be considered for the analysis of specific projects results, as the assessment was constrained by restricted availability of confidential projects deliverables. In some instances, the only publically available information was abstracts and final report summaries from the CORDIS database while no projects websites were still available.

2 Technology state of the art and development trends

2.1 Overview

This section provides an assessment of the state-of-the-art of various technologies that are used to produce heat and power from biomass. Different bioenergy pathways include a number of conversion technologies, based on thermo-chemical (combustion, torrefaction, pyrolysis, hydrothermal processing, gasification) and biochemical/biological (digestion and fermentation) processes. Biorefineries are a rapidly emerging concept integrating a number of biomass conversion technologies in complex systems, producing a range of value-added products (chemicals, materials, food, feed) and bioenergy (biofuels, biogas, heat and/or electricity) in a single facility. Novel promising feedstocks such as aquatic biomass (algae), offers great perspectives for future development from the point of view of large potentially available resources, versatility of production options and technologies that could be used.

Bioenergy technologies are at various stages of maturity, from lab-scale, pilot scale R&D to commercial stage and new technologies are expected to enter the market soon. Further research support is necessary for most technologies to improve their technical performances and achieve cost effectiveness, or to scale them up and demonstrate their technical and economic data in stand-alone systems or in combination and integrated into more complex facilities. The sub-technologies selected for this report are listed in Table 2

Table 2. Sub-technologies for heat and power from biomass for analysis within LCEO.

Sub-technology
Biochemical processes
Anaerobic Digestion
Thermochemical processes
Combustion
Torrefaction
Gasification
Pyrolysis
Hydrothermal processing
New biomass feedstocks
Algae for bioenergy
Integrated processing biomass feedstocks
Algae for bioenergy

2.2 Biochemical processing

2.2.1 Anaerobic digestion

Anaerobic digestion (AD) is the conversion of organic material into biogas by microorganisms under anaerobic conditions. AD includes a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen in four steps: hydrolysis; acidogenesis; acetogenesis; and methanogenesis. Biogas is a renewable fuel that could be used to produce electricity, heat or as vehicle fuel. The biogas produced is a mixture of methane (50 - 70 %), carbon dioxide (30 - 40 %), small quantities of other gases, such as hydrogen sulphide (H_2S) and ammonia (NH_3), and trace amounts of hydrogen (H_2), nitrogen (N_2), saturated or halogenated carbohydrates, organic silicon compounds (e.g. siloxanes), oxygen (O_2) and particles. AD is a technology suitable for using most wet biomass and organic waste, such as agricultural, municipal and industrial organic residues and wastes, sewage sludge, animal fats and slaughtering residues, sewage sludge from wastewater treatment and also aqueous biomass (micro and macro algae) (EPA and NREL 2009). Co-digestion of various feedstocks (e.g. energy crops, organic solid waste, or animal manure) is a common practice that allows to maintain the optimum C/N ratio of the substrate and to maximize the biogas yield. More difficult feedstocks (such as straw, food waste and other residues) might require additional pre-treatment to achieve higher gas yields or post-processing to remove various contaminants.

Anaerobic Digestion occurs under certain conditions (psychrophilic, mesophilic, and thermophilic), which differ mainly based on specific temperatures. **Thermophilic** digestion (50 – 70 °C) requires shorter retention time due to faster degradation at the higher temperature and better pathogen and virus removal than **mesophilic** digestion (25 – 40 °C), requiring lower digester volume, but entailing more expensive technology and higher energy consumption (IEA 2009). Nowadays, mesophilic digesters are the most popular but thermophilic conditions are applied in most of the large-scale centralized biogas co-digesters.

The process may operate as a **wet anaerobic digestion** process, treating low solid content waste that contains up to 20 % dry matter and as a **dry digestion process**, when dry solids content of feedstock is between 20 – 40% dry matter or more. Dry AD systems allow the use of substrates with a high content of crop residues, household waste and wastewater sludge. Dry AD plants offer several benefits, including greater flexibility in the type of feedstock accepted, shorter retention times and lower water usage. AD systems also have less complex system, require less critical equipment (pumps, agitation systems, feeding equipment) and are therefore cheaper and are very tolerant system for contaminants (sand, particles).

Biogas is used for electricity and heat production in electricity only plants, heat only plants or CHP plants. Energy generation options with AD include gas engines, Stirling engines, gas turbines, micro turbines, and fuel cells. AD plants are mostly connected to gas-fired engines for heat and power generation with electrical capacity ranging from tens of kWe up to a few MWe. The heat generated can also be used to meet the local heat demand on farm, or delivered to external users. Generally, a relatively small part of the biogas is used to produce heat only or in industrial applications for steam generation.

Biomethane is currently supplied in Europe as compressed gas from dedicated filling stations for Natural Gas Vehicles (NGV) and public transport applications. Biogas **upgrading** to biomethane has emerged as an option for injection into the natural grid or to be used as vehicle fuel. In comparison to on-site conversion of biogas into heat and/or electricity, the upgrading of biogas to biomethane allows a more flexible use of this resource as it can be used in existing combustion engines and benefit from the Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) refuelling infrastructure. Biomethane can also be used as a feedstock and as an alternative for natural gas to produce a range of bio-based chemicals.

Biogas can be **upgraded** to bio-methane for the injection into the natural gas grids, or for the use as fuel in gas engine vehicles. Biogas upgrading entails the removal of carbon dioxide to increase the energy density as well as the removal of water, hydrogen sulphide and other contaminants to avoid corrosion or other problems in downstream applications. There are several upgrading biogas technologies available including Pressure Swing Adsorption (PSA), Pressurised Water Scrubbing (PWS), physical scrubbing (e.g. selexol, genosorb), chemical scrubbing using amines (e.g. MEA, DEA), Pressure Swing Adsorption (PSA), cryogenic technologies, and separation through membranes. Several biogas upgrading technologies operate commercially, including mostly water/chemical scrubbing and Pressure Swing Adsorption (PSA). Water scrubbing is the most common upgrading technique, followed by organic physical scrubbing and chemical scrubbing based on amine solutions. Cryogenic separation might be of growing importance in case of higher use of biomethane as LNG, benefitting from the integration of methane separation with liquefaction units for the methane (Thrän et al. 2014).

The upgrading technologies commercially available (Van Foreest 2012, Thrän et al. 2014) are:

- **Pressure Swing Adsorption**, where CO_2 is separated by adsorption on solid surface (activated carbon or molecular sieves - zeolites) under elevated pressure (3-10 bar). The carbon dioxide is desorbed from the adsorbent by reducing the pressure;

- **Pressurised Water Scrubbing** (PWS), where carbon dioxide, hydrogen sulphide and ammonia from biogas are dissolved in water at lower temperatures and higher pressures (5-10 bar). The dissolved carbon dioxide is released from the solvent in a desorption vessel at atmospheric pressure;
- **Organic physical scrubbing**, where carbon dioxide is absorbed at high pressure (5-10 bar) in selective organic solvent such as polyethylene glycol instead of water;
- **Chemical scrubbing** to remove hydrogen sulphide and carbon dioxide from biogas using amines at atmospheric pressure. The resultant rich amine is then regenerated by heating to about 160°C;
- **Membrane separation**, where pressurized (5 – 20 bar) biogas passes through a membrane unit permeable to carbon dioxide, water and ammonia, whereas the methane is retained;
- **Cryogenic upgrading**, a developing technology making use of the different boiling points of various gases, particularly for the separation of carbon dioxide and methane.

Electricity conversion efficiencies vary between 30 % and 45 % for gas engines, 25 – 32 % for micro turbines, 30 - 45 % for gas turbines, and 18 – 22 % for Stirling engines, depending on equipment type and size (Mott Mac Donald 2011). The capacity of biogas plants is constrained by the availability of the feedstock within a certain distance from the biogas plant, and is typically in the range of 250 kWe to 5 MWe (IEA 2012a). The economic viability of AD is highly sensitive to feedstock price, process configuration and plant size. While higher capacity plants are more economic, their capacity is limited by the feedstock availability. Combined heat and power production represents a good option to improve the overall efficiency of biogas plants if heat could be used locally or through heat distribution networks. The by-product from AD, the digestate, can be used as fertiliser, just like manure, having the same content of nutrients as manure. This brings additional economic benefits by reducing the use of chemical fertilizers in farms, and reduces nutrient runoff and avoids methane emissions.

AD is a relatively established technology for manure, energy crops or sewage sludge, around TRL 8 - 9. There are a number of AD technologies operational and their technical complexity and associated capital and operational costs depend on the feedstock. AD and biogas upgrading has been successfully demonstrated. There are about 459 biomethane units in Europe with a production of about 1.2 billion m^3 biomethane (from a total of biogas produced of 18 billion 18 billion m^3 methane equivalent in 2015), and 697 filling stations and 340 plants feeding into the natural gas grid.

2.3 Thermochemical processing

2.3.1 Biomass combustion

Bioenergy production is largely based on mature, **direct combustion** technology using solid, gaseous and liquid biomass. Biomass combustion occurs in both small-scale combustion in stoves and boilers and large-scale combustion for heat, electricity or CHP applications. Biomass combustion in a boiler is a standard technology to generate **electricity** via a steam turbine. Small-scale combustion occurs in stoves and small boilers for traditional heating in the residential sector or for industrial heat production. Biomass **heating** is a mature, commercial-scale technology and it is competitive with heat produced from fossil fuels. There are many different kinds of stoves available, including open fireplace, closed fireplace, firewood space heater etc., with a capacity between 5 and 15 kW. Traditional heating systems in a stove, using wood logs, have low efficiency (10 - 30 %) and high emissions (especially particulate matter). Modern biomass technologies, with high efficiencies (90 %), are available and include efficient wood log, wood chips, or pellet burning. High efficiency, low emission systems include automatic feeding systems and advanced control systems, but at higher cost. Small-scale automated heating boilers with high efficiency are used for central heating and are equipped with a water heat exchanger and connected to a heating water circuit based on wood chips or wood pellets. Biomass heat can also be produced in co-generation power plants, supplying heat from industry or from district heating network. Overall efficiencies of around 80 - 90 % are possible (IEA 2012a, JRC 2013).

Heat and power production from biomass is based on **various technologies** including Grate Boilers (GB), Bubbling Fluidised Bed Combustion (BFBC) or Circulating Fluidised Bed Combustion (CFBC) boilers, coupled with steam turbine system. Grate boiler coupled with steam turbine system is the standard and simpler technology for small to medium-scale (1 to 10 MWe) power generation, offering low investment and operating costs. Fluidised bed technologies (including Bubbling Fluidised Bed Combustion - BFBC and Circulating Fluidised Bed Combustion - CFBC boilers) are commercial technologies that ensure high efficiency, low emissions and high fuel flexibility. Fluidised bed technologies offer the advantage of large fuel flexibility (biomass type, moisture content) and higher conversion efficiency although with higher capital and operating costs (IEA 2009, IEA-ETSAP and IRENA 2015). CBFC technology is used in small-scale to large power generation with lower fuel properties and higher fuel flexibility. Combustion technology can utilize controlled systems with automatic fuel feeders to reduce Particulate Matter (PM) and pollutant emissions. Latest improvements offer new plants with advanced steam parameters and high efficiency (EPA and NREL 2009, IEA-ETSAP and IRENA 2015).

The **scale** of operation is a very important factor for heat or power from biomass systems, with specific capital and operating costs increasing as plant capacity reduces. The efficiency of power generation depends on the scale of the operation. Power generation efficiencies using steam turbines are in the range of 25 % to 35 % for steam turbines biomass plants, with efficiency somewhat lower than those of conventional fossil-fuelled plants of similar scale. Biomass plants with large capacities usually have advanced steam parameters and high efficiencies. Thus, the efficiency of electrical generation alone ranges from about 10 % for small CHP plants (< 1 MWe steam-engine) to 24-38% for plants between 10-50 MW and 32-42% for plants with a capacity above 50 MW for steam-turbine combined with advanced fluidised bed combustion technology (IPCC 2011, IEA 2012a, IEA-ETSAP and IRENA 2015). Co-generation is an effective way to significantly increase the overall efficiency of a power plant (and hence its competitiveness) when a good match exists between heat production and demand. Co-generation plants might offer typical overall efficiencies in the range of 80% to 90%. Various technologies are available for electricity production based on biomass combustion: steam turbine process (for plants higher than 2 MWe), ORC and steam engines (200 kWe - 6 MWe) and Stirling engines (below 100 kWe). Stirling engines are promising applications of small scale electricity production from biomass using external combustion engines. The heat is not supplied in the cycle by the internal combustion but transferred from outside through a heat exchanger. Electric efficiency can reach 12 % to 15 %. Stirling engines are being demonstrated in CHP applications (Obernberger and Thek 2008, IEA 2009).

Biomass combustion is a well-**established** commercial technology for heat and power generation (TRL 8 - 9). Bioenergy production can be competitive in some circumstances and when cheep feedstock is available, or when deployed with financial support. The key to the deployment of these technologies is the availability and reliability of sustainable feedstocks. The economies of scale are significant for biomass plants, although the overall size of biomass plants is limited by biomass availability, the high transportation cost for biomass feedstock and logistic issues. Thus, the opportunities for large plants may be limited. The economic performances and the deployment of biomass CHP plants are also limited by the local heat demand (for heating cooling of industrial heat) and by its seasonal variation (IEA-ETSAP and IRENA 2015, LCICG 2012, Mott MacDonald 2011).

Biomass **co-firing** consists of combusting biomass and fossil fuels, mostly coal but also natural gas. Biomass co-firing with coal in existing boilers is a cost-effective and efficient option of electricity and heat production from biomass in pulverised coal-fired, grate-fired boilers, stationary and circulating fluidised bed boilers. There are three different concepts for co-firing biomass in coal boilers:

- direct co-firing, using a single boiler with either common or separate burners;

- indirect co-firing, a gasifier converts solid biomass into a gaseous fuel and the gas produced is burnt in the same furnace as the coal;
- parallel co-firing, in which a separate boiler is used for biomass, and its steam generation is then mixed with steam from conventional boilers.

Co-firing biomass in coal-fired power plants offers advantages with respect to the use of biomass in dedicated plants that include higher efficiency, lower pollutant emissions and lower costs. This approach makes use of the existing infrastructure of the coal plant and thus requires only relatively minor investment in biomass pre-treatment, handling and feeding equipment without noticeably affecting boiler efficiency. Biomass properties pose several challenges to coal plants that may affect their reliability and lifetime, causing increased ash corrosion and deposition (slagging and fouling) on the surfaces of the boiler and affecting flue gas cleaning equipment and Selective Catalytic Reduction (SCR) system efficiency (JRC 2013, IEA-ETSAP and IRENA 2015, IEA 2009).

Direct co-firing has been successfully achieved up to about 15 % biomass in pulverised coal-fired boilers, while fluidised bed boilers can substitute higher levels of biomass. Higher percentages of biomass (50 - 80 %) may be used in co-firing with extensive pre-treatment (e.g. torrefaction), with minor changes in the fuel handling system. **Indirect and parallel co-firing** alternative options allow to the avoidance of biomass-related issues (moisture, ash composition, etc.), but require additional infrastructure and are more capital intensive. Indirect co-firing with pre-gasification of the biomass has now been demonstrated in both coal power plants and in coal gasification plants. Although they are more expensive because of the additional technical equipment required, this option allows for a greater variety and higher percentages of biomass to be used. Biomass co-firing in modern, large and highly-efficient coal power plants results in high biomass conversion efficiency that ranges between 35 – 44 %, depending on the plant technology, size and specific biomass feedstock. This is significantly higher than the efficiency hat can be achieved in small (<10 MW) and medium-scale (10-50MW) dedicated biomass power plants with efficiencies of 25 - 35 %. Apart from the higher efficiency, the economies of scale of large power plants will also lead to lowered costs for the energy provided per unit of biomass fuel use. Higher efficiencies of 46 % to 52 % could be reached with indirect co-firing in Biomass Integrated Gasification Combined Cycle (BIGCC), but more R&D and cost reduction efforts are needed for this technology to reach commercial status (Mott MacDonald, 2011, Irena 2012, IEA-ETSAP and IRENA 2015, IEA 2009, JRC 2013).

Biomass co-firing has been successfully **demonstrated** with many technology options and with a wide range of biomass feedstocks (wood and herbaceous biomass and crop residues) and is now in full commercial operation in many installations worldwide. Typical co-firing plants, equipped with pulverised coal boilers, stoker boilers, cyclone boilers, bubbling and circulating fluidized bed boilers, are in the range from approximately 50 MWe to 700 MWe (IEA Bioenergy Task 32, 2018). However, the use of coal for energy generation is expected to decrease in line with the goals of decreasing GHG emissions and thus the number of coal generation units will decrease, reducing the potential for biomass co-firing.

2.3.2 Torrefaction

Torrefaction is a thermochemical upgrading process consisting of biomass heating in the absence of oxygen at atmopsheric pressure and temperatures typically ranging between 250-320°C, leading to a release of moisture and partial release of volatile compounds. Torrefaction has the potential to become an important pre-treatment technology and so improve the biomass to a high quality solid fuel. Torrefaction produces a high quality solid biofuel with higher heating value or energy density, lower moisture content, good hydrophobic behaviour, improved grindability and reactivity and more uniform properties (Chen et al 2015, Van der Stelt et al 2011). Biomass torrefaction is used as a pre-treatment step for biomass conversion techniques such as combustion and gasification.

Torrefaction can be classified into light, mild and severe torrefaction processes. The heating value of the torrefied biomass increases from 19 MJ/kg to 21-23 MJ/kg for torrefied wood or event to 30

MJ/kg in the case of complete devolatization resulting in charcoal. The torrefaction degree depends typically on the time that a (dry) biomass particle resides in the torrefaction reactor and on the temperature inside the reactor. **Different reactor** technologies are available for torrefaction: rotating drum reactor, screw reactor, multiple hearth furnace, microwave reactor, moving/fixed bed or fluidized bed reactor. The selection of technology needs to be done based on the characteristics of the feedstock, or alternatively, the feedstock needs to be pre-processed (Cremers et al 2015). The control of the temperature profile and residence time of biomass in the reactor is crucial for an efficient process and optimal product quality. Ensuring product quality and consistency is a challenge, due to uneven biomass quality (particle size and composition), heat transfer rate, temperature, and residence time, requiring process optimisation (IEA 2015).

Biomass torrefaction can create new markets and trade flows as commodity fuel and increases the feedstock basis. Torrefaction improves the combustion properties and the suitability of biomass for co-firing in coal fired power plants and has the potential to enable higher co-firing shares (JRC 2013, IEA 2015). Torrefaction improves the **suitability of biomass** for co-firing in coal fired power plants and decreases the costs for handling, storage and transport. Torrefaction of agro-residues appears to be more complicated due to the challenging physical and chemical characteristics. Torrefaction process results in feedstock and energy losses and increased cost. The energy required for the drying and torrefaction process is delivered by the combustion of torrefaction gas, or from additional auxiliary fuel. Integration of the torrefaction process with existing biomass-fired boiler plants, such as district heating plants, utility boilers or wood industry boilers, offers a possibility to benefit from energy streams and feedstock handling available.

Biomass densification (pelletization) is a process to create compact biomass fuel with uniformly sized solid particles such as pellets, briquettes and logs with higher energy density. The quality of densified pellets strongly depends on the particle size, moisture content, and process parameters. Pelletizing torrefied biomass, which densifies the material to pellets or briquettes, brings a number of advantages in terms of superior combustion characteristics, resistance to degradation and moisture uptake. Additional advantages of pelletizing torrefied biomass, in comparison to torrefied biomass chips as the intermediate product, refer to transport, handling and storage. Torrefied biomass could improve the gasification efficiency and reduce the tar formation due to its high heating value and low volatiles content. Torrefaction is also an effective method for reducing the water, acid, and oxygen contents of bio-oil when derived from fast pyrolysis of torrefied biomass (Chen et al. 2015, Eseyin et al 2015).

Biomass torrefaction has been proven at pilot scale and a number of demonstration and (semi)commercial facilities are in operation (Cremers et al 2015). Torrefaction technology is not yet fully commercially available, but the first **demonstration** projects are in operation (e.g. Andritz-ECN, at Stenderup, Andritz ACB in Frohnleiten, Stramproy at Steenwijk, Topell at Duiven, etc.). Further development of torrefaction technology is needed to overcome certain technical and commercial challenges (Star Colibri 2011, JRC 2013, IEA 2015).

2.3.3 Pyrolysis

Pyrolysis is the thermochemical conversion of biomass into a bio-oil, gas, and solids (bio-char) in the absence of oxygen at lower temperatures than combustion or gasification, around 450 – 600 °C (typically 500 °C). The ultimate goal of this technology is to produce high-value bio-oil for competing with and eventually replacing non-renewable fossil fuels. The extent of decomposition depends on process parameters, reactor configuration and feedstock. The exact fraction of each product depends on the temperature heating rate and the residence time. Pyrolysis process can be categorized as slow or fast pyrolysis, distinguished by different residence times in the reactor. Fast pyrolysis has been developed in recent years as a fast and flexible method to provide liquid products from biomass. While slow pyrolysis favours the production of bio-char, fast pyrolysis, at moderate temperatures (450 – 500 °C) and short residence times (< 5 s) favours the production of bio-oil. Pyrolysis is based on various types of reactors including Bubbling Fluidised Beds rectors, Circulating Fluidised bed (CFB), screw-type reactors or based on microwave pyrolysis (IEA 2009, Bridgwater 2018a).

Fast pyrolysis produces mostly **bio-oil**, along with small amounts of biochar and gases, like hydrogen, carbon monoxide, and carbon dioxide. Bio-oil is the desired product and has higher market value potential. High pyrolysis temperature and longer residence time increase the biomass conversion to gas while lower temperature and longer vapour residence times favour the production of charcoal. The proportions of each phase and product composition depend on the process design, the chemical conditions, temperature and reaction rate within the pyrolysis reactor. Up to 75 % of the biomass is converted to bio-oils, 10 - 15 % of biochar and 10 - 15 % of permanent gases. The by-products obtained (char and gas) are used within the process to provide the process heat requirements (Mott MacDonald 2011, Star Colibri 2011, Bridgwater 2018a).

Bio-oil is a **complex mixture** of hundreds of chemicals and oxygenated hydrocarbons with high water content with a calorific value of about 17 MJ/kg. Pyrolysis oil has about twice the energy density of wood pellets, which could make it particularly attractive for long-distance transport. The bio-oil composition is influenced by several factors: feedstock properties, heat transfer rate, reaction time, temperature profile, and/or the addition of catalysts. Bio-oil is miscible with some solvents such as methanol and acetone, but totally immiscible with petroleum-derived fuels. Bio-oil can be a substitute for fuel oil or diesel for heat and power production, in many applications including boilers, engines and turbines. The use of pyrolysis bio-oil in diesel engines can be a valuable approach for small scale, CHP applications. Although bio-oil is a promising alternate to fuel oil, its direct applications without chemical upgrading is limited due to its high viscosity, high water and ash contents, low heating values, solid content, chemical instability, and high corrosiveness. Research is also under way to explore the possibility of mixing pyrolysis oil with conventional crude oil in existing oil refineries (JRC 2013, Mott MacDonald 2011, Star Colibri 2011, Bridgwater 2012).

Besides the heat and power applications, bio-oil can also be **upgraded** to feedstock for advanced biofuels, converted to fuel additives, to chemical intermediates and final products. Pyrolysis can also be used as a pre-treatment step for gasification and biofuels production. **Biorefineries** offer considerable scope for optimisation of fast pyrolysis processes, that require the development of the various processes in order to optimise an integrated system. The main challenges for development rely on the integration of pyrolysis process in complex systems such as biorefineries that offer prospects for product utilisation.

Bio-oil upgrading aims to improve bio-oil quality for the production of chemicals or hydrocarbon biofuels (Bridgwater 2018a). **Bio-oil upgrading** to transport fuels is challenging because of the high oxygen and water content of bio-oils. Bio-oil can be upgraded following physical, chemical and catalytic pathways. The main methods for **upgrading** bio-oil to transport fuels include: hydrodeoxygenation of bio-oil; catalytic vapour cracking of fast pyrolysis vapours followed by hydrodeoxygenation and/or use into a conventional oil refinery Fluid Catalytic Cracking (FCC); or gasification to syngas followed by synthesis to hydrocarbons or alcohols. Bio-oil can be deoxygenated by two potential routes: the oxygen can be thermally cracked from the bio-oil in the form of water and carbon oxides, or it can be removed as water by the addition of hydrogen. The bio-oil could be converted through gasification into a synthesis gas that is then cleaned to remove particles, alkaline salts, HCl, H_2S, COS, CS_2, NH_3, and HCN. Many chemical pathways are possible to produce gaseous and liquid fuels and chemicals from syngas (Bridgwater 2018b).

Pyrolisys is adequate for small decentralised fast pyrolysis plants of 50,000 to 250,000 tonnes or 1 to 3 MWe per year for production of bio-oil liquids to be transported to a central processing plant. The implementation of large projects could involve multiple small modules (JRC 2013, Mott MacDonald 2011). Pyrolysis and bio-oil upgrading technology is still in the pre-commercial **demonstration** phase, with considerable experience been gained from several pilot and demonstration plants (Fortum in Finland; BTG Empyro in NL; Pyrogrot in Sweden, etc. (Meier et al., 2013, JRC 2013). Biomass pyrolysis has been successfully demonstrated at small-scale, and several large pilot plants or demonstration projects (up to 200 ton/day biomass) are in operation or at an advanced stage of construction. The technology to produce upgraded pyrolysis oil, developed originally for heat, power, and food industry applications, are at pre-commercial, initial demonstration stage at TRL 3 - 5 (LCICG 2012).

2.3.4 Hydrothermal processing

Hydrothermal processing is a thermochemical process that involves thermal disintegration of biomass in the presence of water, at high temperature and pressure. The process converts biomass into a solid (bio-char), a liquid (bio-oil or bio-crude), or a gas (e.g., hydrogen, methane), with one intended output, depending on the type of process used (Kumar el al 2018, Reißmann et al 2018). Different types of hydrothermal processes occur depending on pressure, temperature and residence time that are crucial reaction parameters: Hydrothermal Carbonization (HTC), Hydrothermal Liquefaction (HTL) and Hydrothermal Gasification (HTG) (Reißmann et al 2018). The nature and yield of products from hydrothermal technologies depends on factors such as the feedstock type, catalyst, and process conditions (temperature, pressure). Hydrothermal processes (HTP) appear to be a promising technology platform for processing **wet biomass** and residues.

Table **3** shows the typical parameters for the main types of HTP.

Table 3. Typical parameters of the hydrothermal processing options

HTP type	Temperature	Pressure
HTC – Hydrothermal Carbonization	180–250 °C	2–10 MPa
HTL – Hydrothermal Liquefaction	300–350 °C	5-25 MPa
HTG – Hydrothermal Gasification		
Catalytic/low-temperature	350-450 °C	25-40 MPa
Non-catalytic/high-temperature	>500 °C	25-40 MPa

Source: Reißmann et al 2018 Kumar el al 2018.

HydroThermal Carbonization (HTC) converts biomass into a value-added product (hydrochar) at a comparatively low temperature (180–250 °C) and pressure (2–10 MPa). The resulting product, a solid hydro-coal and bio-char, has carbon content similar to lignite with mass yields varying from 35% to 60% and can be used as a solid biofuel, fertilizer and soil conditioner.

HydroThermal Gasification (HTG) is a process that involves a reaction at high temperature (above 350 °C) and high pressure (25-40 MPa) and produces a flue gas rich in hydrogen or methane, depending on the reaction conditions. Hydrothermal gasification entails three main types: aqueous phase refining, catalytic gasification in a near-critical state, and supercritical water gasification. Catalytic gasification of biomass in a near-critical state occurs at 350–450 °C and produces CH_4 and CO_2 in the presence of a heterogeneous catalyst promoting CO hydrogenation to CH_4. Gasification at a lower temperature is desirable for process efficiency and is often carried out by catalyst that improves the yield and quality of output. Supercritical water gasification (SCWG) uses water at a supercritical state in the range of 600–700 °C to generate mainly H_2 and CO_2 with/without a catalyst. The products from hydrothermal gasification include CO_2, H_2, CO and CH_4, with small amounts of C_2H_4 and C_2H_6. (Kumar et al 2018, Reißmann et al 2018).

HydroThermal Liquefaction (HTL), also known as hydrous pyrolysis, is a biomass to bio-liquid conversion route that involves the thermochemical conversion of biomass in the presence of water at high temperature (300–350 °C) and pressure (5–20 MPa). Hydrothermal Liquefaction produces liquid bio crude, along with the gaseous, aqueous and solid phase by-products. The liquid bio-crude or HTL oil can be used as a bio-fuel and as a substitute for crude oil for chemical products manufacture (Kumar et al 2018, Reißmann et al 2018). HTL oil produced has low oxygen content as opposed to other processes like fast pyrolysis. Conditions such as temperature, pressure, particle size, and reaction times influence the conversion of biomass into bio-oil. The use of catalysts in hydrothermal liquefaction processes is intended to improve process efficiency by reducing char and tar formation. The exact mechanisms of the HTL process still remain unclear mainly due to the complexity of the process and the large number of possible intermediate reactions. Biomass is first broken up into fragments by hydrolysis, and then degraded into smaller compounds by dehydration, dehydrogenation, deoxygenation and decarboxylation. Some complex chemicals may be afterwards synthesized by repolymerization. Biocrude oil generated in the repolymerization process usually contains acids, alcohols, aldehydes, esters, ketones, phenols and other aromatic compounds (Dimitriadis and Bezergianni 2017, Gollakota et al. 2018, Kumar et al 2018).

HydroThermal Liquefaction is suitable for the production of **biocrude** from biomass with high and variable moisture content such as woody biomass, agricultural and forestry residues, industrial wastes, food wastes, algae, etc. HTL has the competitive advantage of processing not only dry but also wet biomass, requiring no feedstock drying. Biomass derived biocrude produced by liquefaction have high heating value, low oxygen content and low moisture content depending on the type of biomass feedstock and the operating conditions – temperature, solvent type, catalyst, residence time and biomass-to-solvent ratio. HTL proves to be energy efficient as it entails lower temperatures than those reached during pyrolysis. The choice of the temperature depends on the biomass feedstock, solvents, catalysts and other operating parameters. The use of **catalyst** seems to be an important factor that could significantly increase the biocrude production and reduce the solid residue yield. The role of catalyst is mainly to suppress the formation of char, increasing the yield of liquid products and reducing the condensation and/or repolymerization reactions of the intermediate products. Biocrude has high viscosity, high corrosive activity, and relative low stability requiring further upgrade of HTL products. The aqueous phase generated through HTL process can be treated anaerobically or via catalytic hydrothermal gasification to produce methane-rich or hydrogen-rich syngas (López Barreiro et al. 2013, Dimitriadis and Bezergianni 2017, Kumar et al 2018).

Hydrothermal processing is now in the transient state from lab-pilot scale (TRL 4-5) to **pilot**-industrial scale (TRL of 5-6) with some projects closer to demonstration. More research is necessary, however, for optimizing the technology and achieving commercial operation. Technological gaps with respect to various plant components include reactor design for process development and optimization and the selection of adequate materials to avoid corrosion in the extreme environment in the reactor. There is a wide range of potential process designs and the optimal process parameters and other important influencing factors need to be established.

2.3.5 Biomass gasification

Gasification is a thermo-chemical conversion process of biomass into a fuel gas (syngas), at high temperature (700-1500 °C), by partial oxidation with limited oxygen. The **syngas** is a gas mixture of carbon monoxide, hydrogen, methane and carbon dioxide as well as light hydrocarbons (ethane and propane), and heavier hydrocarbons (such as tars), and other gases, such as sulphidric and chloridric acid, or inert gases (such as nitrogen). Gasification is an intermediate step between pyrolysis and combustion. Gasification is a highly versatile process, being able to convert any biomass feedstock into fuel gas. There is a wide range of possible configurations for biomass gasification, depending on the oxidation agent (air, oxygen or steam), process heating (direct or indirect), pressure level (atmospheric pressure or elevated pressure), or reactor type (moving bed, fluidised bed or entrained flow, up-draught and down-draught reactors). The selection of the most appropriate gasification process depends on the properties of the available feedstock, the final application of gas and other factors.

The gasification products are strongly influenced by gasification agent, temperature, pressure, heating rate and fuel characteristics (composition, water content, particle size). Air-based gasifiers typically produce a gas with a high nitrogen content and a low energy content (4 - 5 MJ/m^3), while oxygen or steam gasifiers produce a syngas with higher CO and H_2 concentration and higher energy content (9 – 19 MJ/m^3). Steam increases the H_2 content by the water gas shift reaction

(Mott MacDonald 2011, IRENA 2012, Molino et al 2016). Fluidised bed gasifiers are more tolerant to feedstock properties and require less pre-treatment than entrained flow gasifiers, but produce more tars and light hydrocarbon gases, which need more complex gas purification systems (Star Colibri 2011). Extremely high temperatures (~ 4000°C) during **plasma gasification** allow the complete dissociation of the feedstock into syngas and complete breakdown of tars and other gas contaminants. This technology is particularly promising for waste gasification (industrial or municipal waste, hazardous wastes, tyres etc.) producing a chemically inert slag itself that is safe to handle. **Indirect gasification** consisting in the separation of the gasification and combustion processes in different reactors, allows the production of a N_2-free gas without the need for an air separation unit, making it suitable for synthesis applications.

Gasification gas contains a range of contaminants, such as tars, sulphur, chlorine compounds, alkali metals, heavy metals and particulates, depending on the feedstock, gasifier design and the gasification process. The contaminants generally need to be removed, since they can impact on the operation of downstream processes. Therefore, **gas cleaning and conditioning** is a crucial step in biomass gasification facilities. The removal of tars is a particularly challenging issue. The removal of syngas contaminants could be achieved through primary methods, such as gasifier design, operating conditions (temperature, pressure), gasifying agent, in-bed catalysts/additive. Secondary methods are also available, including physical processes (cyclones, filters, scrubbers, electrostatic precipitators) or through thermal-catalytic processes (thermal cracking, partial oxidation, catalytic reforming, plasma processes).

The available technologies to purify the synthesis gas, are classified according to the temperature: hot (T > 300 °C), cold (T < 100 °C), and warm gas cleaning. Several mature hot gas clean-up technologies could remove complex tars (thermal, catalytic cracking, plasma and physical separation) and particulate matter (barrier filtration, inertial and electrostatic separation). Hot gas clean-up technologies could be used for sulphur removal (physically or chemically adsorption), ammonia (selective catalytic oxidation or thermal catalytic decomposition), alkali (condensation) and alkali and chlorine (solid adsorption). Cold gas clean-up processes are typically wet processes, entailing water scrubbing and various chemical and/or physical solvent processes, as well as biological and chemo-biological processes (Obernberger and Thek 2008, IEA 2009, FreedomCAR 2009, JRC 2013). Temperature reduction allows alkali to condense and agglomerate into small particles (Woolcock and Brown 2013). Water discharge from wet scrubber, heavily contaminated, requires chemical and/or biological waste water treatments in order to be recirculated or discharged. Various cleaning technologies were tested in various systems (Mott MacDonald 2011).

The fuel gas product, including hydrogen, can be used in internal and external combustion **engines**, **boilers**, **fuel cells**, for heat and power or to produce **Synthetic Natural Gas (SNG)**, methanol, **Fischer–Tropsch** liquids and other **chemicals**. Syngas generated can be used to produce heat and power directly. Nowadays, biomass gasification is mainly used for efficient heat and power production and co-firing at small- and medium-scale plants. Syngas can be used in internal combustion gas engines operating at electrical conversion efficiencies between 30 - 35 %, in gas turbines (up to 40 % efficiency), in gas and steam turbine combined cycles (up to 42 %), or in fuel cells (50 - 55 %) (IEA 2009, JRC 2013).

Typical gasification plant capacities range from a few hundred kW for heat production, and from 100 kW to 1 MWe for CHP with a gas engine, and up to 10 MW for gas turbines systems operating at higher efficiency than a steam cycle. At larger scales (>30 MWe), gasification-based systems can be coupled with a gas turbine with heat recovery and a steam turbine (combined cycle) in a Biomass Integrated Gasification Combined Cycle (BIGCC) technology, thus offering higher efficiency (IFC 2017). The BIGCC concept is a promising technology, ensuring higher electrical efficiency, of 40 - 50 % for 30-100 MW plant capacity, although more complex and costly (JRC 2013). The combined cycle technology based on natural gas is well established technology in many plants, but the efficiency and reliability of biomass gasification still needs to be proven.

New developments are under way toward large-scale synthesis of biofuels and chemicals: methanol, ethanol, hydrogen, or synthetic natural gas, hydrocarbon fuels (gasoline, kerosene, diesel, DME), etc.). Synthesis applications usually require more intensive cleaning, water-gas-shift

(WGS) reactions, gas reforming, catalytic conversion steps, etc. Several technologies are currently available on the market. For example, ethanol can be produced from biomass syngas through syngas fermentation or through syngas thermochemical catalytic conversion, which produces a mixture of methanol and ethanol. Biomethane production requires methanation of the clean syngas, followed by a CO_2 removal. Syngas can be converted to methanol and then further via DME to synthetic gasoline or directly via methanol to gasoline. The main processes to produce biodiesel from syngas are based on the Fischer–Tropsch synthesis (IFC 2017, Molino et al 2016, IEA-ETSAP and IRENA 2015). The Fischer–Tropsch is a well-established process for the production of synfuels.

Although several projects were implemented worldwide, biomass gasification is still at **demonstration** stage, reaching TRL 6 - 7. Further technology development requires demonstration at scale and proof of reliable, continuous and long-term operation (LCICG 2012, IEA 2012a). The experience acquired from the worldwide application of coal gasification is relevant to biomass gasification. BioSNG is an unproven technology at full scale, around TRL 4-5, which requires innovation to integrate various components into a full scale plant. BIGCC is still in the pilot stage, around TRL 4 - 5, and requires significant R&D before reaching full maturity (LCICG 2012, IEA-ETSAP and IRENA 2015).

2.4 Algae for bioenergy

Algae currently receive increasing interest as potential source for the production of biomass for multiple uses. Algae offer several advantages compared to land-based biomass, including high **photosynthetic efficiency and high yield**, as well as the possibility to grow on non-fertile land using a variety of water sources (i.e. fresh, brackish, saline) and additional CO_2 capture potential. Land-based ponds, both as free standing farms or in combination with land-based aquaculture systems could reach higher productivities (up to 50 tonnes of dry matter per ha per year). A wide range of marketable co-products can be extracted from algae, e.g. chemicals and nutrients, along with the production of biofuels, within a biorefinery concept. One of the most challenging aspects for commercial production is to mitigate the enormous amounts of water and nutrients required to grow and process algal feedstocks. Wastewater recycling is essential to minimize freshwater and chemical nutrients consumption (FAO 2009, van der Velde et al, 2017, Laurens et al. 2017).

Macroalgae (seaweed) are multicellular plants growing in salt or fresh water, in near-shore marine waters, attached to rocks, dedicated growth structures, like anchored lines/netting, or other substrates. Different farming systems have also been employed onshore and land-based facilities. Depending on the species, macroalgae contain different proportions of lipids, proteins and carbohydrates. Macroalgae can be exploited for production of chemicals with high economic value and for the production of biomethane and biofuels via various conversion processes (Jiang et al. 2016).

Microalgae could be cultivated on land in open or closed reactors, allowing accurate and continuous monitoring and control of process parameters. Open Raceway Ponds (ORP) are inexpensive and easy to operate and maintain, but there are several drawbacks including lower productivity, poor light utilization, high water evaporation losses and high risk of contamination. The Photo Bio Reactors are closed systems with controlled conditions, which allow the culture of single-species of microalgae with low risks of contamination, higher productivity and reduced contamination, but rely on complex design and require high investment and maintenance cost. **Harvesting** microalgae requires different steps and approaches, depending on the features of the selected strains and desired concentration. The main processes include thickening (flocculation), separation and dewatering (filtration through a membrane and centrifugation) that increase the algal concentration from 0.02% - 0.07% (open ponds), or 0.14% - 0.7% (photobioreactors) to 10-25%, followed by drying.

Possible **bioenergy pathways from algae** include their conversion to biogas, bioalcohols, bio-oil, biodiesel and bio-hydrogen. These include various processes such as oil extraction, biochemical (AD, fermentation, etc.) and thermo-chemical conversion (gasification, pyrolysis, hydrothermal liquefaction) technologies. Algae can produce high amounts of lipids, hydrocarbons and other complex oils. The extraction of oil can be performed through chemical solvent extraction (dry biomass, 60 - 98 %) and supercritical fluid extraction (wet biomass 10 - 25 %). Further processing options include either transesterification to produce FAME biodiesel or hydrotreating the oils to generate a renewable diesel.

The high content of moisture and carbo-hydrates in macroalgae make them suitable for **wet conversion** methods, including anaerobic digestion and fermentation. AD of algae for biogas production is one of the most viable technologies considering the high moisture (85 – 90 %), high carbo-hydrates content and low amount of lignin of algae. AD of microalgae does not require a pure culture nor does a specific compound need to be produced. There are still some technical issues to be addressed, such as the high salinity and sand accumulation over time (Laurens et al. 2017). The biogas yields (and the adjustment of the C:N ratio) can be increased through co-digestion of some species of algae with nitrogen rich substrates (such as manure) and manipulation of the microbial composition of the inoculums. Algae can also be a suitable feedstock for bio-hydrogen production via photo fermentation or dark fermentation by means of a pure or mixed culture of hydrogen-producing bacteria or via a combination of dark, photo fermentation and AD in three stage processes. The integration of algae production with wastewater treatment is a feasible pathway for the large-scale production of algae, providing opportunities for the treatment of waste streams and the use of organic substrate such as nutrients (N, P) from wastewater (Redwood et al, 2009, Murphy et al, 2015, Rocca et al. 2015).

Algae can be suitable feedstocks for bio-oil via **thermochemical conversion** pathways. The high-temperature, thermochemical conversion processes of algae include direct pyrolysis of dry algae or hydrothermal processing (hydrothermal liquefaction - HTL) of algae in water slurries. **Pyrolysis** produces bio-oil (or biocrude), bio-char, vapours and an aqueous phase upon condensation. The bio-oil yields may significantly vary depending on the macroalgae composition and operating conditions. A major limitation to pyrolysis is the high moisture content (70-80 %) of algae, requiring significant energy for drying. Hydrothermal liquefaction allows algae to be processed without drying, using supercritical water at high temperature and high pressure (Demirbas 2010, Milledge and Heaven 2014, López Barreiro et al. 2013, Rocca et al. 2015).

Hydrothermal liquefaction at high temperature and high pressure is a wet process, better suited for algae due to the extremely low algae concentration The partial dewatering of algae solutions to the level of 10-20% dry solids, adequate for HTL, is less energy intensive than pyrolysis that requires drying to >90% dry solids. The bio-oil (biocrude) produced from HTL is similar to oil crude, but biocrude is oxygenated, acidic, and contains various contaminants that require additional processing. The HTl biocrude may be suitable for use as heavy fuel oil, but significant upgrading is required before it can be used as a transportation fuel through catalytic hydrotreatment and catalytic cracking. After upgrading, biocrude could be used into a traditional refinery. Wastewater treatment and recycling potential nutrients is a key element for HTL processing. **Catalytic Hydrothermal Gasification (CHG)** process carried out at subcritical water conditions can be also employed as a catalytic upgrading pathway to recover energy and nutrients from the rich aqueous phase solution and produce methane and carbon dioxide gases. The product gas can be burned to produce CHP for the hydrothermal processing system (Laurens et al. 2017).

Algae conversion for bioenergy is still at laboratory or pilot-scale, TRL 3-6, with many activities focussing on algae cultivation harvesting and various processing routes; therefore, algae production for bioenergy is still far from commercialization. Algae production require process improvement to enable efficient production at commercial scale. The cultivation of microalgae is limited to large open ponds or lagoon, while commercial production in Photo Bio Reactors (PBR) is limited. The existing designs of Open Raceway Ponds and Photo Bio Reactors have been investigated so far at small/experimental scale, algae production have not been implemented at the large scale and they are still far from commercialization. Macroalgae are currently cultivated in large open ponds or lagoon in Asia, to produce food and additives for food, pharmaceuticals, cosmetics and chemical industry. There are also commercial cultures of microalgae for high-value, low volume food, feed and nutraceuticals in Asia, US, Israel and Australia (LCICG 2012, Milledge and Heaven 2013, Vigani et al, 2015, Rocca et al. 2015).

2.5 Biorefineries

Biorefining refers to the sustainable processing of biomass into a range of biobased products and bioenergy, defined as "***sustainable processing of biomass into a spectrum of marketable products and energy***" (IEA Bioenergy Task 42). The goal of a biorefinery is to transform biological materials into multiple products using a complex combination of technologies and processes. The biorefinery concept, that that integrates various biomass conversion processes to produce fuels, power, and value-added chemicals from biomass, is similar to the one of conventional oil refineries: to produce a variety of fuels and other products (IEA 2012b) and denotes integrated biorefineries i.e. multi-feedstock, multi-product, multi-process.

Biorefineries integrate production of **high-value, low-volume and low-value, high-volume products** that are produced in a variety of processes designed to maximize / optimize the use of resources and minimize the waste streams. The high-value products enhance the cost efficiency of the whole refinery, while the high-volume fuels help to meet the energy demand and to reduce the overall cost. Biorefineries could be a key factor in the transition to a bio-based economy, allowing efficient and cost effective processing of biomass to a range of products such as food, feed, bio-based products, biochemicals, and bioenergy (electricity, heat and/or biofuels). Biorefineries can either derive final, marketable products directly or create intermediate products that can be further processed into new end products (MEF 2009, JRC 2013).

A variety of concepts are being currently developed with new products and routes still being identified. Biorefineries include combinations of several thermochemical and biochemical processes. **Thermochemical processing** consists on pre-treatment (e.g. drying, size reduction, torrefaction), conversion (e.g. combustion, pyrolysis, gasification, and hydrothermal processing), cleaning and upgrading (reforming, separation) to final end-product. Biomass can be converted into liquid or gaseous forms for the production of electric power, heat, chemicals, or gaseous and liquid fuels. **Biochemical conversion** processes include a sequence of processes that involve pre-treatment (hydrolysis, steam explosion), conversion to sugars, photosynthesis and fermentation of intermediates using biocatalysts, separation purification and final processing. The integration of such processes makes them able of delivering a number of chemical or material co-products in addition to heat and power. Several new biorefinery concepts defined rely on the principle of cascading use, where the highest value products are extracted first and biofuels and bioenergy are final products.

A classification for the different existing and emerging biorefinery systems is difficult to make and to achieve general acceptance due to the complexity of multiple possible configurations, used feedstocks, conversion technologies and final products. A Bioenergy Task 42 developed a biorefinery classification system that consists in four main features which are able to identify, distinguish and characterise the different biorefinery systems:

- **platforms:** intermediates that are able to connect different biorefinery systems and their processes (e.g., C5/C6 sugars, syngas, biogas, syngas, electricity and heat);
- **products**: energy (e.g., biomethane, biofuels, electricity and heat) and products (e.g., chemicals, polymers, food, and feed);
- **feedstocks:** energy crops (e.g., oil crops, sugar crops, starch crops, lignocellulosic biomass, marine biomass) and residues (lignocellulosic residues, oil based residues, organic residues);
- **conversion processes**: mechanical (e.g., fractionation, extraction, pressing, pretreatment), biochemical (e.g., fermentation, AD, enzymatic conversion), thermochemical (e.g., gasification,

pyrolysis, hydrothermal processing) and chemical (e.g., acid hydrolysis, synthesis, esterification, methanisation, hydrogenation, hydrolysis).

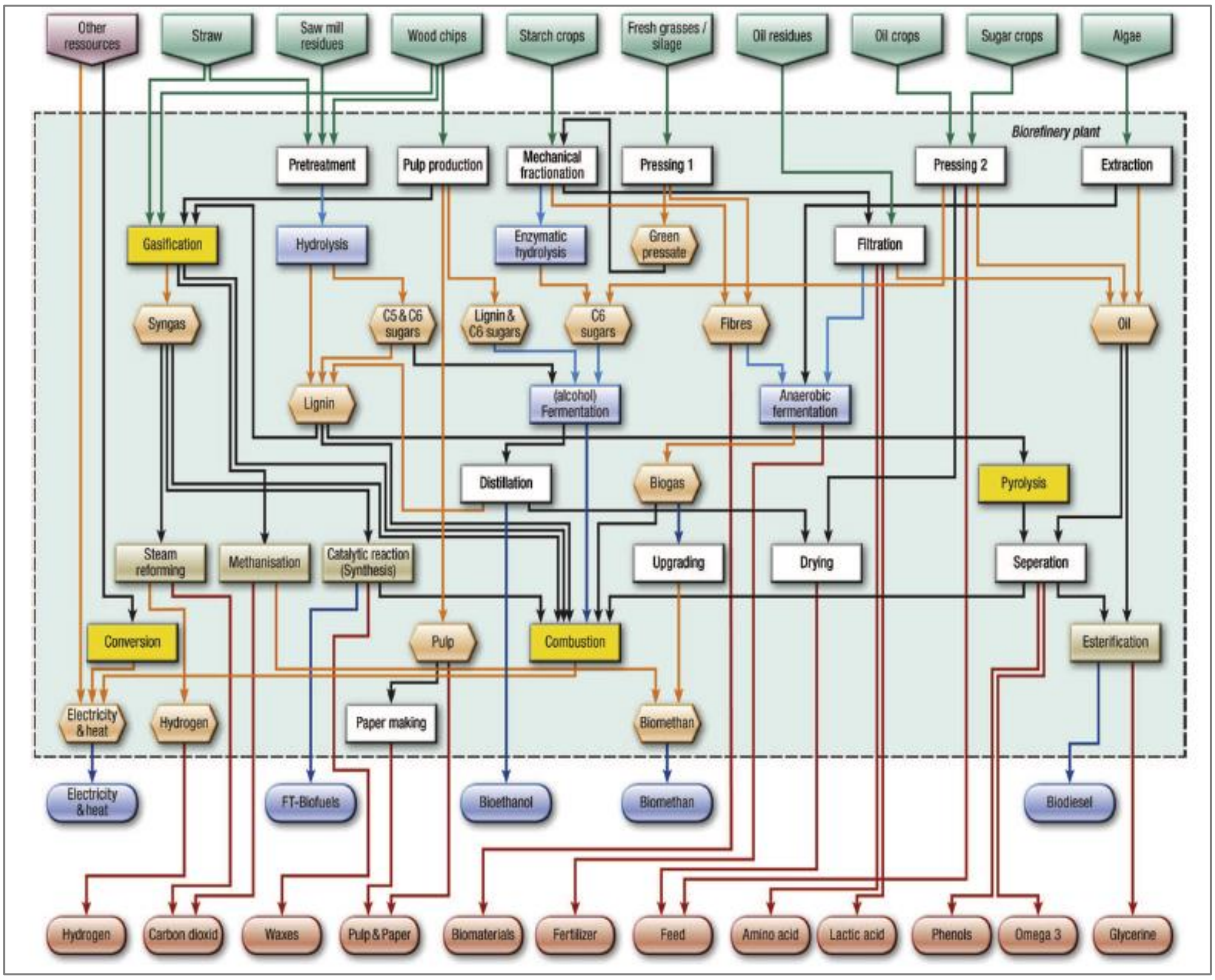


Figure 1. Biorefinery concepts

Source: de Jong and Jungmaier 2015.

Currently, many different biorefinery concepts are being developed, ranging from simple concepts, using one feedstock (e.g., vegetable oil) and producing two or three products (e.g., biodiesel, animal feed, glycerine) based on available commercial technologies. However, other biorefinery concepts are very complex using many different feedstocks (e.g., algae, grasses or wood) that produce a broad spectrum of different products (e.g., phenol, fatty acids, bioethanol, biodiesel) using technologies that are not yet commercial. Biorefineries are usually referred to as of first generation (based on food crops such as sugar starch or oil crops) or second generation (based on lignocellulosic, non-food materials, such as agricultural residues, grasses or wood) or third generation (using algae biomass). The most established type of biorefineries are first generation, while second generation and third generation refineries are still under development due to technical or economic challenges (de Jong and Jungmaier 2015.

Table 3 provides an overview of the main characteristics of different biorefineries. The stage of development of biorefineries ranges from conceptual to large-scale demonstration with the focus either on chemicals/materials or bioenergy, e.g. bifuels bio-heat and bio electricity as main products. The deployment of the new biorefineries depends on the technical maturity of a range of processes to produce biobased materials, biochemicals and energy and on the extent of integration of different technologies and processes (Van Ree and Annevelink, 2007, Cherubini et al., 2009, Rødsrud et al., 2012, IEA 2012b). The cost effective production of advanced lignocellulosic biofuels has been a major driver for the development of biorefineries. The economic competitiveness biorefineries is based on the production of high-value co-products in addition to low-value bioenergy (JRC 2013). Figure 2 presents the high complexity of various biorefinery concepts, based on different feedstock, using different processing technologies and their combinations and leading to different products.

Table 4. Overview of the main characteristics of different biorefineries

Concept	Type of feedstock	Main technology	Phase of development	Products
Conventional biorefineries	Starch (corn, wheat, cassava) and sugar crops (sugarcane, sugar beet), wood	Pretreatment, chemical and enzymatic hydrolysis, catalysis, fermentation, fractionation, separation	Commercial	Sugar, starch, oil, dietary fibers, pulp and paper
Whole crop biorefineries	Whole crop, cereals (rye, wheat, maize)	Dry or wet milling, biochemical conversion	Pilot plant (and Demo)	Starch, ethanol, DDGS*
Oleochemical biorefineries	Oil crops	Pretreatment, chemical catalysis, fractionation, separation	Pilot plant, Demo, commercial	Oil, glycerin, feed
Lignocellulosic feedstock biorefineries	Ligno cellulosic rich biomass (e.g., straw, grass, wood)	Pretreatment, chemical and enzymatic hydrolysis, catalysis, fermentation, separation	R&D/Pilot plant (EC), Demo (USA)	Cellulose, hemicelluloses, lignin
Green biorefineries	Wet biomass: green crops and leaves (grass, clover, sugar beet leaf)	Pretreatment, pressing, fractionation, separation, digestion	Pilot plant (and R&D)	Proteins, aminoacids, lactic acid, fibers
Marine biorefineries	Aquatic biomass (microalgae and macroalgae)	Cell disruption, product extraction and separation	R&D, pilot plant and Demo	Oils, carbohydrates, nutraceuticals

* DDGS - Distiller's Dried Grains with Solubles
Source: de Jong and Jungmeier 2015.

3 R&D Overview

3.1 EU R&D framework programmes

This section presents an overview on the most relevant EU-funded projects in the area of biomass heat and power. It focuses on the Horizon 2020 programme for research and innovation (2014-2020) and its predecessors: the former Seventh Framework (FP7) and Intelligent Energy Europe (IEE) programme, as well as SET-Plan flagship projects supporting biomass technologies. The data on IEE projects was gathered from the IEE projects database.. The info on FP7 and H2020 projects was collected from CORDIS database (European Commission Community Research and Development Information Service) and other sources, 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 by the Temporary Working Group (TWG) on Bioenergy and Renewable Fuels (SET Plan 2018).

The data collection was set up for defined biochemical and thermochemical categories including the sub-technologies which are used for the production of heat and power from biomass. The sub-technologies which were presented in section 2 include: combustion, torrefaction, anaerobic digestion, gasification, pyrolysis, and hydrothermal processing. Furthermore, projects indicated as bio-refineries were also considered in this analysis, including integrated biomass conversion into a range of products such as bio-chemicals and bio-materials, energy carriers, heat, electricity, and fuels. The projects, denoted as support actions for bioenergy, which were dedicated to coordination and support actions with the general goal of boosting the development and deployment of bioenergy technology applications. Special attention has been given also to novel marine feedstock (algae) that can contribute to the enlargement of the feedstock base for bioenergy that involve the development and tailoring of a number of conversion technologies including integrated biorefineries for the production of energy, biochemical and bio-materials.

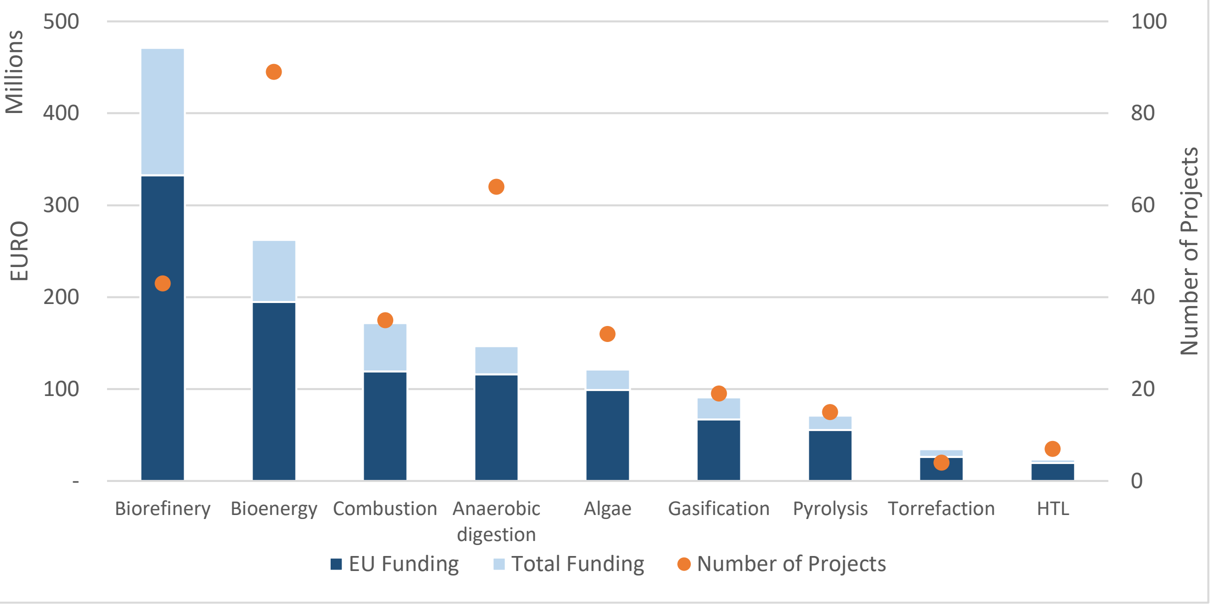


Figure 3. EU funding for bioenergy technologies and number of projects

The analysis of the EU funded projects revealed that a number of 314 projects on biomass for heat and power relating to technology development have been identified, totalling 1.4 billion Euros and receiving 1 billion Euros as funding from the EU, addressing general bioenergy issues under the IEE programme (IEE 2018), FP7 and H2020 RTD EU programmes (Cordis 2018).

These projects addressed general bioenergy issues, biomass combustion, torrefaction, AD, biomass gasification, pyrolysis, hydrothermal liquefaction, algae production for energy purposes and biorefineries. The number of bioenergy projects and the distribution of funding for different sub-technology is provided in

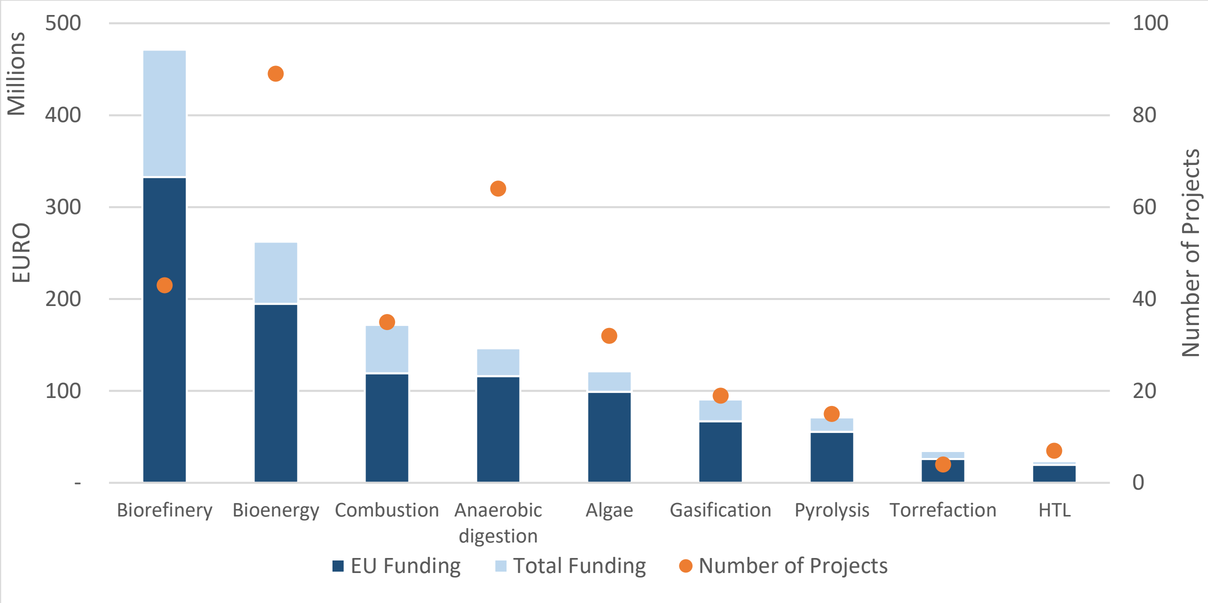
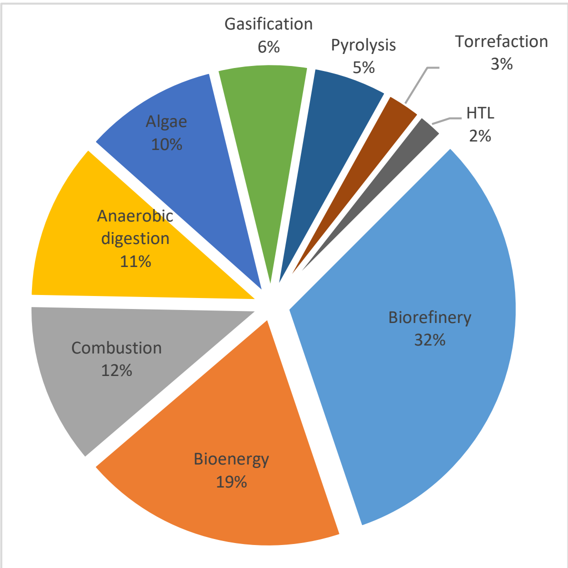


Figure 3. Significant funding has been provided for biorefinery projects, AD, combustion and gasification. Hydrothermal processing has received less funding, as being a new technology, the research focussing on lab and pilot scale investigations. Other technologies are new and they are still at the first stages (algae for bioenergy production). High number of projects was funded to focus general bioenergy issues, followed by AD, gasification and combustion. There was a large increase last years in the number and total funding on biorefineries that aimed at developing various biorefinery concepts. Compared to general bioenergy issues and AD, fewer projects but with higher value addressed biorefineries.



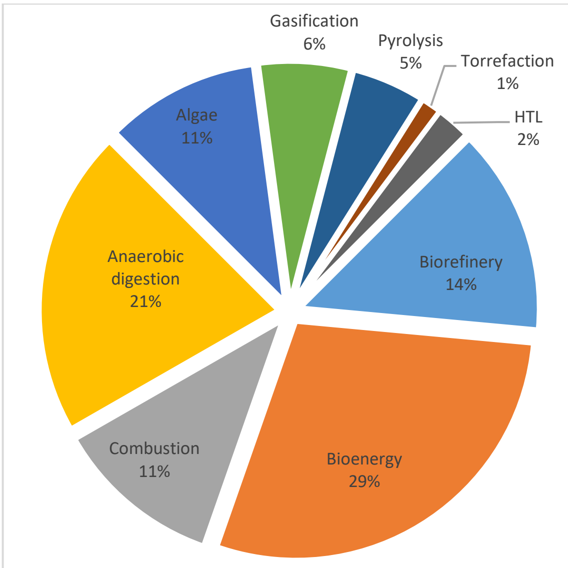


Figure 4. Share of technology-related bioenergy projects
in terms of EU funds received (left) and number of projects (right)

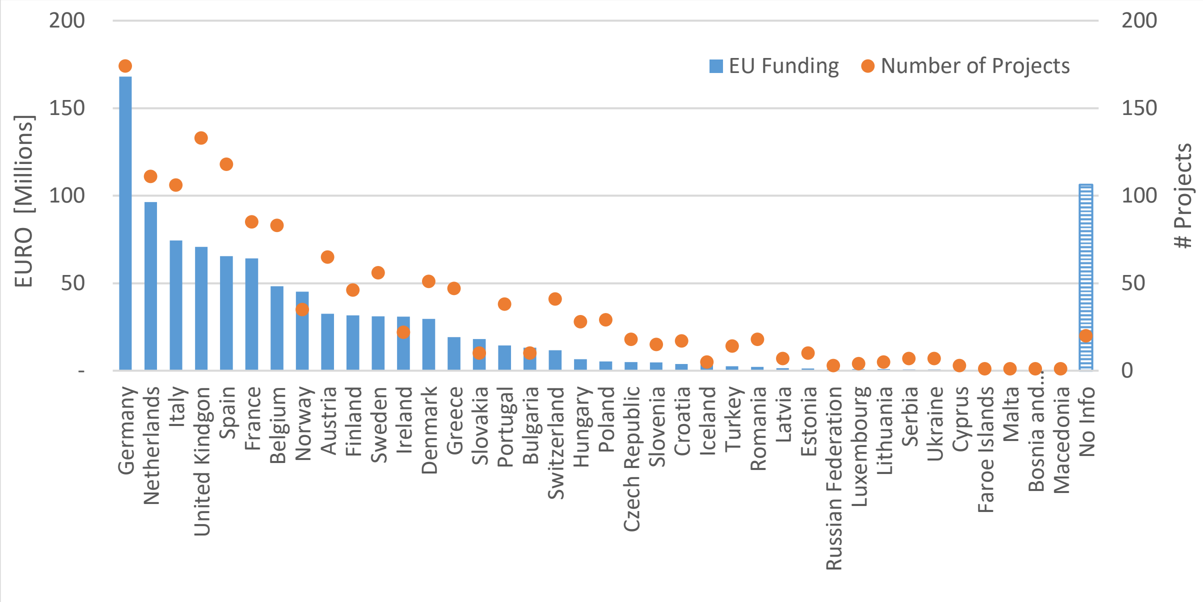


Figure 5. Total of the EU funding of the H2020 and FP7 Programmes grouped by country

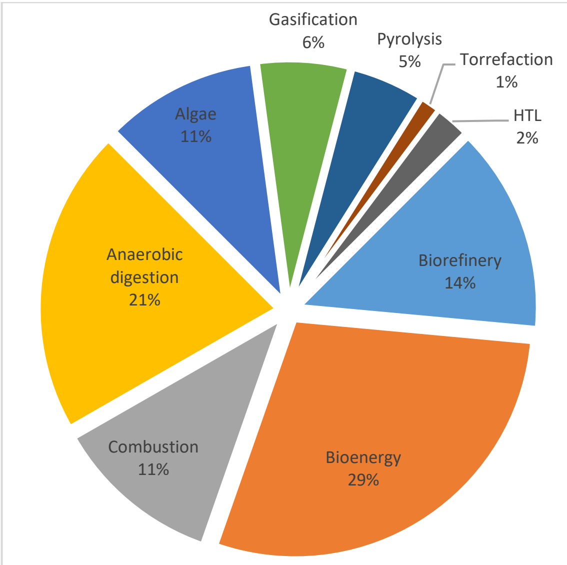


Figure 4 displays the share of various bioenergy projects in terms of the EU funds received and number of projects awarded. It is possible to observe that biorefinery, bioenergy and AD projects respond to around 60% of all EU funded projects. The biorefinery projects received almost 1/3 of the EU funds, although the number of projects reaches only 13% of the total. Bioenergy projects are in higher proportion (27% of the total); however, they received less than 20% of all EU funds. The AD projects correspond to almost 1/5 of the projects and 11% of the total EU funds.

In general, the projects are executed by multiple institutions located in different countries. Figure 5 shows the distribution of the total EU funding related to the H2020 and FP7 Programmes grouped by country. Germany is the leading country in terms of received funding (16% of the total), followed by the Netherlands (9%), Italy (7%), UK (7%), Spain (6%) and France (6%). The remaining European countries received altogether around 36% of the total EU funding. Note that 10% of the destination of the EU funds is not reported in the respective project description available at the CORDIS portal.

3.2 Cross-cutting bioenergy issues

A large number of projects addressed various aspects of bioenergy production, such as biomass potentials, markets, logistics, and policies, in order to promote the development and large scale deployment of bioenergy production. A group of projects addressed the development of cooperation on bioenergy, to establish structural cooperation between national bioenergy research programmes. They also targeted to support bioenergy technology development and implementation, policy actions and market strategies and identify and create synergies among related R&D activities (**BRISK**, **S2BIOM, Biofuels TP, FACCE SURPLUS**) and to support the contributions of biofuel and bioenergy stakeholders to the Strategic Energy Technology (SET)-Plan (**ETIP Bioenergy-SABS**). Some projects aimed to encourage and facilitate cooperative research in biomass across Europe (**ERIFORE**), or to establish post-graduate level curricula (**BioEnergyTrain**) in key bioenergy disciplines. A project aimed to harmonise the calculations of GHG emissions for electricity and heat from biomass (**BioGRACE**).

The aspects of whole bioenergy chains were investigated in several projects focussing on the identification, evaluation and development of whole bioenergy chains to promote the implementation of sustainable supply chain management practices or to support the sustainable delivery of non-food biomass feedstock (**BIOTEAM, SecureChain, Biomob**). Several projects focused on developing and promoting local supply chains in nature parks (**BIOEUPARKS**), identifying, evaluating, initiating and upscaling bio-energy chains (**MAKE-IT-BE**, **GRACE**), developing local supply chains of short rotation crops (**SRCPLUS**) and promoting efficient biomass value chains through the use of best practices in the provision of biomass (**AGRIFORVALOR, ENABLING, PromoBio**). The issue of logistics was addressed in several projects through the implementation of biomass logistic centres in the agro-industry (**SUCELLOG**) for food and non-food products (**AGROinLOG**) and through the identification of priority locations of biomass logistic and trade centres (**BioRES**) for increasing the demand for woody bioenergy products.

GIS tools have been developed to provide information about sustainable biomass resources and costs available in Mediterranean countries (**Biomasud Plus**), to provide information on the regional supply and demand of wood chips, including information on biomass potential, on current plants using wood chips (**BASIS**), as a user-friendly regional energy planning tool (**BEN**) and as decision support system which allows both public decision makers and private operators to identify the most suitable sites for biomass plant installations (**BioEnerGIS**).

Some projects aimed to identify opportunities for commercialisation of applied research and improve biomass mobilisation (**BIOMOB, BIOPROM**) or to contribute to the development and application of European quality standards and certification schemes for biomass (**PELLCERT, SolidStandards, QUALITY WOOD)** in order to develop the bio fuel market and to overcome non-technical barriers for the implementation of bioenergy. Some projects aimed to demonstrate high-efficient polygeneration (**ENERCOM**) or the use of heat (**Coolheating, Woodheat, Bio-Heat**) and to promote large scale investment to bring bioenergy close to the market (**BESTF, BESTF2**).

Few projects focussed to quantify the role of biomass can play to meet the 2020 targets (**BIOMASS FUTURES**), to promote a more efficient and harmonized policy regulation framework, needed to boost the market-pull of bio-based products (**STAR-ProBio**). Guidelines were formulated for the development of a European bioenergy trade strategy (**BIOTRADE2020PLUS**) and to develop integrated policies for the mobilisation of resource efficient bioenergy value chains in order to contribute towards the 2020 and 2030 bioenergy targets (**BIOMASSPOLICIES**).

Several projects aimed at increasing the production, mobilisation and utilisation of biomass (**AFO, greenGain, BIOENERGY FARM uP_running, Woodheat Solutions, BIOMASSTRADECENTRES**), including through the exploitation of biomass from marginal lands (contaminated, abandoned, fallow land) (**FORBIO, SEEMLA**). Other projects focussed on the promotion of best practices (**FOREST, BestRES, BioRegions**) and the new business models (**Bioenergy4Business, PromoBio**). Few projects aimed at developing of platforms of stakeholders to address societal, environmental and economic challenges related to biomass

(**BIOREG, BIOVOICES**) and for better communication on the various bio-based products and applications and their benefits.

Several projects addressed bioenergy market aspects, to raise awareness and provide information, know-how transfer among stakeholders (**CODE),** to support market implementation and regional bioenergy initiatives (**MIXBIOPELLS, PromoBio, EUBIONET, BIOMASSTRADECENTRES**), to help remove barriers to market uptake (**ADVANCEFUEL**) to promote cross-border investments (**CROSSBORDERBIOENERGY**).

3.3 Cross-cutting bioenergy issues: international projects

The International Energy Agency (IEA) has established Technology Collaboration Programmes to provide a framework for international collaboration in energy technology R&D, demonstration and information exchange. **IEA Bioenergy** facilitates co-operation to develop new and improved energy technologies and introduce them into the market. A number of 23 parties participate: Australia, Austria, Belgium, Brazil, Canada, Croatia, Denmark, Finland, France, Germany, Ireland, Italy, Japan, the Republic of Korea, the Netherlands, New Zealand, Norway, South Africa, Sweden, Switzerland, the United Kingdom, the United States) and the European Commission. IEA Bioenergy aims to increase knowledge and understanding of bioenergy systems to facilitate the commercialisation and market deployment of environmentally sound, socially acceptable, and cost-competitive bioenergy, and provide advice to policy and industrial decision makers. IEA Bioenergy addresses a full range of bioenergy aspects, including biomass feedstocks, biomass combustion and co-firing, energy recovery from waste, gasification, direct thermochemical liquefaction, biogas, advanced biofuels, also focussing on sustainable biomass markets, international bioenergy trade and the climate change effects of biomass and bioenergy systems (IEA Bioenergy 2018).

IEA Bioenergy **Task 43 Biomass Feedstocks for Energy Markets** provides analyses and policy-relevant information on biomass feedstock, biomass markets and socioeconomic and environmental consequences of feedstock production. Participating countries are: Australia, Belgium, Canada, Croatia, Denmark, Finland, Germany, Ireland, Netherlands, Norway, Sweden and the USA. The Task addresses commercial, near-commercial and promising feedstock production systems in agriculture and forestry. The primary focus is on sustainable land use and land management of biomass production. The Task carries out studies on trade-offs, compatibility and synergies between food, fibre and energy production and the bio-economy. Research priorities include i) landscape management and design for bioenergy and bio-economy; ii) developing effective supply chains; iii) governance sustainability of bioenergy supply chains (IEA Bioenergy Task 43 2018).

The **International Renewable Energy Agency (IRENA)**, as intergovernmental organisation, serves as a platform for international cooperation, knowledge sharing, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the adoption and sustainable use of renewable energy (RE) toward sustainable development, energy access, energy security and low-carbon economic growth (IRENA 2018). **IRENA** carries out RE technology briefs, cost and benefits studies, provides RE statistics, global atlas of resource potential, etc. IRENA and the Abu Dhabi Fund for Development (ADFD) have collaborated on a **joint Project Facility** to support replicable and scalable RE projects in developing countries. ADFD committed $350 million in concessional loans to RE projects. IRENA developed the **Sustainable Energy Marketplace** to scale up investments in renewable energy and energy efficiency in developing and emerging countries to meet global climate and sustainable development goals. The IRENA Project Navigator is an online platform providing comprehensive, easily accessible, and practical information, tools and guidance to assist in the development of bankable projects.

The IEA Bioenergy project on **Bioenergy RES Hybrids** aims to make a review of the current status of bioenergy RES hybrids and identifies those areas in the energy system where such hybrids can play a strategic role. The main scope of this project is to monitor, review and evaluate information from ongoing R&D&D programs and operating hybrid systems to create a better understanding of the the current state of bioenergy hybrid technologies. The project plans to identify promising hybrid solutions and perform a cost and market assessment for selected hybrid processes. The project will finally draft preliminary roadmaps seeking for new renewable solutions to facilitate transition to energy system towards future sustainable energy system.

In the United States, the Department of Energy's (DOE's) **Bioenergy Technologies Office (BETO)** oversees a research, development, demonstration, and deployment program that focuses on how to improve five technical elements of bioenergy in order to lead to greater use of bioenergy in the US. The program focuses R&D efforts on feedstock supply, conversion, and the improvement of power generation technologies. The **Conversion Research and Development Program** of BETO supports early-stage applied research in technologies for converting biomass feedstocks into finished liquid transportation fuels—such as renewable gasoline, diesel, and jet fuel—co-products or chemical intermediates, and biopower. To achieve this goal, BETO is exploring a variety of conversion technologies that can be combined into pathways, from feedstock to product. The Office of Energy Efficiency and Renewable Energy (EERE) supports technical collaborations to promote global deployment of US clean energy technologies.

The **Bioenergy Systems for Viable Stationary Applications** (BSVSA) program provides support to overcoming the technical and cost barriers involved in the integration of locally-sourced biomass into stationary energy systems. By delivering clearly-defined cost and technical performance outcomes, the BSVSA program's research, analysis and demonstration activities will increase business revenue and market opportunities while reducing energy generation costs. To unlock the full market potential of the bioenergy value chain in Canada, the program's resources and projects are planned through to 2018-19. The creation of a robust, next-generation domestic bioenergy industry is one of the important pathways for providing sustainable, renewable energy alternatives.

Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources, FNR) in Germany coordinates research, development and demonstration projects on renewable energy within the framework of the funding programme *Renewable Resources* of the German Federal Ministry of Food and Agriculture. FNR also manages the part of the Energy and Climate Fund (EKF) which is earmarked for bioenergy-related R&D. FNR also collects up-to-date knowledge on this topic and makes it available to scientists, decision-makers and public. FNR coordinates German activities related to renewable energy at European level, e.g. through participation in EC-funded projects.

The **ERA-NET Bioenergy** funded by the European Commission under FP6 (2004-2010), is a network of national funding organisations that support bioenergy projects. ERA-NET Bioenergy has so far funded ten calls: on clean (small-scale) combustion, biomass gasification gas cleaning, short rotation coppice, sustainable forest management and optimised use of resources, biogas and energy crops, small-scale heat and power production from solid biomass, integrated biorefinery concepts, innovative bioenergy solutions and biobased economy projects. A consortium of nine EU Member States and Associated Countries (Austria, Denmark, Finland, Germany, Netherlands, Poland, Spain, Sweden and the UK) is implementing the ERANET cofund activity entitled **Bioenergy Sustaining the Future (BESTF)** that provides funding to collaborative bioenergy projects that prove at least one innovative step and result in demonstration at a pre-commercial stage. The purpose of combining the 2 ERA-NETs is to provide additional value compared to national funding by supporting transnational research and knowledge exchange, and to thus increase the use of biomass for energy. So far, BESTF and BESTF2 have launched 2 calls and supported bioenergy demonstration projects that fit into one or more of seven EIBI value chains.

BESTF3 aims to implement a joint programme that demonstrate enhanced bioenergy technologies, leveraging public-private partnerships to manage the risks and share the financing of close-to-market bioenergy projects and encourage collaboration across the EU. **BESTF3** main call was launched on 1 December 2015 using the **ERA-NET Cofund mechanism** to support pre-commercial bioenergy projects that demonstrate collaboration, innovation and industry focus. **A Joint Call for Proposals** has been launched in October 2016 including 11^{th} Joint Call for Research and Development Proposals of the ERA-NET Bioenergy and 1^{st} additional Joint Call for Research and Development Proposals of the BESTF3 on the topic: *Bioenergy as part of a smart and flexible energy system* to fund innovative, transnational research, development and innovation projects. Key elements include novelty beyond the state of the art and industry commitment. Projects may focus on different bioenergy value chains or energy uses and address the economic, environmental and social sustainability. Projects should address solutions that enable full or improved usage of the biomass feedstock and/or put the focus on residues, by-products and solutions that integrate the production of different products/intermediates (chemicals, materials, bioenergy incl. biofuels).

The **European Industrial Bioenergy Initiative (EIBI)** is one of the industrial initiatives launched under the SET Plan, which is the technology pillar of the EU's energy and climate policy. European Industrial Bioenergy Initiative aims to accelerate key energy technologies for a low-carbon future under the SET Plan, with risk and investment shared by the EU, Member States and industry. The EIBI aims to contribute to the commercial availability of advanced bioenergy at large scale by 2020, aiming at production costs which allow competitiveness with fossil fuels at the prevailing economic and regulatory market conditions. EIBI further aims to contribute to advanced biofuels (i.e. sustainable biofuels with a broader material base and/or better end product properties than biofuels currently on the market) covering up to 4% of transportation energy needs by 2020.

3.4 Biochemical processing

3.4.1 Anaerobic digestion

Several projects aimed to promote the development of biogas production and of a biomethane market (**ATBEST, BiogasAction, BIOSURF, GreenGasGrids, ISABEL, Record Biomap, BIO-METHANE REGIONS**), by creating web-based platforms (**GERONIMO**) to provide access to the relevant information on technology, financial support, and tools to help farmers plan, invest and/or upgrade biogas plants, as well as for predicting the techno-economic feasibility for digestion using various substrates (**BiogasIN, FARMAGAS, SUSTAINGAS, BIOPROFARM**). Some projects focussed on the biomethane production and addressed the legal, organisational and financial barriers for biomethane injection into the natural gas grid and its use in transport (**BIOMASTER, UrbanBiogas, BIO-METHANE REGIONS).**

Various project investigated the improvement options for biogas production to optimise the bio-methanisation and to increase the biogas yield through enzymes of agricultural organic matter in order to produce energy for decreasing the energy cost (**DEMETER, OptiMADMix**). Some projects focussed to develop of small-scale biogas installations that enable on-site treatment of feed left-overs of farms and various organic wastes from agro-food industry (**BioEnergy Farm II, LEGUVAL, VegWaMus CirCrop**). A two-phase (acid/gas) anaerobic process was also investigated, where the acidogenic and the methanogenic stages are separated to allow optimization of both stages (**PHASESPLIT**). While most projects focussed on the development and improvement of mesophilic anaerobic digesters (**OptiMADMix**), few projects addressed thermophilic and low-temperature AD (**Lt-AD, 3CBIOTECH, PLASCARB**) and studied the microbiology of bacteria and the effects of various conditions (**Waste2bioHy, SMART TANK**).

Different projects addressed the AD of various residues, including food waste, brewers' spent grains, citrus fruit residues, wineries' effluents, waste from fish farms, residues from food and beverage industry, animal waste and wastewaters from food and drinks sector, aquaculture or from slaughterhouses (**AD-WINE, BiFFiO, ADAW, FABBIOGAS, Lt-AD, ORION, VicInAqua)**. Biogas innovative concepts and approaches for wastewater treatment plants were investigated (**POWERSTEP, LTANITRO**). Some projects focussed on the use of AD of crops to produce biogas (**CROPGEN**), assessing biogas yield based on several raw materials as substrates, including cellulose-rich materials (straw, wood, grass) (**GR3**). They aimed to optimise and demonstrate innovative approaches to improve biogas yield and energy output and to develop and demonstrate an automatic monitoring for agricultural biogas plants (**AD-WISE, ANAMIX, PHASEPLIT**).

Pre-treatment methods were also investigated to enable the co-digestion for municipal, agricultural and other organic waste to enhance the production of biogas, including biological and thermal treatments and addressed the issue of enzymatic degradation of biomass (**DEMETER, WASTE2GO, BIOMAN, MICRODE, THERCHEM, VALORGAS**). Different biomass pre-treatment methods were tested to minimise energy losses and better reactor designs were investigated (**OptiMADMix**). Pre-treatment methods also addressed valorisation of poultry or pig manure to reduce the ammonia emissions or aimed to sanitise sludge for AD and further use in agriculture (**ROUTES**). Some projects focussed to develop monitoring plant performance and control systems for AD plants based on a real-time volatile fatty acid measurement system (**OPTI-VFA, AD-WISE**), to control the plant automatically and reacting in real-time to variable loading or toxic events **(SHEPHERD)** or to control the use of biogas in biogas engines (**CONDIMON**).

Many projects addressed the AD of various biomass streams to produce biogas for electricity and heat (**F2W2F, BioROBURplus**). Several projects focussed on producing biogas to natural gas quality to be injected into natural gas grid (**Bin2Grid**), or biogas upgrading and reforming of biogas to be used in micro gas turbines or fuel cells (**BioROBUR, Prometheus-5, DEMOSOFC**) with the production of hydrogen (**BIONICO, BioROBURplus, H2AD, Waste2bioHy**) or value-added chemicals (**ENGICOIN**). The issue of heat use from biogas plants was also addressed to increase the efficiency of biogas production (**BiogasHeat**).

The issues of digestate treatment and valorisation were addressed to produce balanced fertilizers and obtain liquid fertilizers with high organic matter content, for transforming the digestion effluents into bio-fertilisers (**INEMAD, BIOFERLUDAN**). Some projects focussed to develop processes for converting biodegradable fractions of agri and industrial waste as well as municipal and animal solid waste into high value-added products, biogas and organic based fertilizer (**3CBIOTECH, BIOWASTE4SP, PHARM AD, WASTE2GO BIOGAS3**). Some projects aimed to demonstrate innovative concepts and design schemes of wastewater treatment (**LTANITRO, BIOWET, PHASEPLIT, 3CBIOTECH**) and carbon extraction and nitrogen and phosphorus recovery (**BIOFERLUDAN NUTREC, PLASMANURE, ADD-ON**). A project addressed the removal of micropollutants or pharmaceutical residues from sludge and wastewaters (**PHARM AD**).

3.4.2 Anaerobic digestion: international projects

The IEA Bioenergy Task 37 Energy from Biogas addresses the technical, economic and environmental aspects of biogas production and utilisation. Task 37 covers the AD of biomass feedstocks including agricultural residues (e.g. manure and crop residues), energy crops, waste waters, the organic fraction of municipal of solid waste and industrial organic wastes. Task 37 addresses the whole biogas chain from feedstock collection and pre-treatment to biogas upgrading, biofertiliser application and process chain sustainability. Task 37 focuses on: i) sustainable digestion of substrates, associated reactor configurations and utilisation of biogas; ii) externalities of biogas systems; iii) technical support to policy makers and to the public. The country participation includes Australia, Austria, Brazil, Denmark, France, Finland, Germany, Ireland, Korea, Norway, Sweden, Switzerland, the Netherlands, United Kingdom. The work will address: biogas production from wastes, residues and by-products, international applications of biogas facilities, reactor configurations and operating parameters, biogas upgrading systems, gas grid injection processes, and methods of greening of the gas grid and *s*mart grid applications*.* The analysis of socio-economic aspects of biogas utilisation include the real cost of biogas systems, including the benefits and disadvantages such as methane leakage (IEA Task 37, 2018).

Biogas production from wet-waste biomass, wastewater treatment and landfill gas recovery is expanding in a number of countries. Biogas upgrading to biomethane is increasing, for the use as a vehicle fuel or for injection into the natural gas grid. Worldwide, biogas is produced primarily by landfill based plants or small-scale family digesters. Biogas support programmes have been carried out in low-income countries to develop small, domestic-scale systems to provide biogas for cooking, as an alternative source to reduce firewood consumption avoid deforestation and decrease indoor air pollution. Several countries in Asia (China, Thailand, India, Nepal, Vietnam, Bangladesh, Sri Lanka and Pakistan) have large programmes for domestic biogas production (REN21 2016, Kapoor et al 2013, Vögeli et al 2014). **China** had an estimated 100,000 modern biogas plants and 43 million residential-scale digesters in 2014, generating about 15 billion m^3 of biogas, equivalent to 9 billion m^3 biomethane (324 TJ), producing heat and fuel, used primarily for cooking. The **Medium-and-Long Term Development Plan for Renewable Energy** requires reaching by 2020 about 80 million household biogas plants, 8000 large-scale biogas projects with an installed capacity of 3000 MW and an annual biogas production of 50 billion m^3 (REN21 2016, Jingming 2014). In the last years, modern biogas plants have been built, with the installed electricity capacity of biogas plants reaching 330 MW in 2015 and 350 MW in 2016 (Laurens et al 2017).

In **India**, the **National Biogas and Manure Management Programme (NBMMP)** is being implemented for the promotion of small-scale biogas plants for producing fuel for cooking. **NBMMP** provides for setting up of family-type biogas plants mainly for rural and semi-urban/households, that generates biogas from cattle dung and other bio-degradable materials. Biogas generation aims to achieve the following benefits: (i) provide clean fuel for cooking and lighting; (ii) use of digested slurry from biogas plants; (iii) improvement of sanitation. In 2014, there were about 4.75 million farm size operational biogas plants, equivalent to a potential of about 12 million family size biogas plants, which could generate more than 10 billion m^3 biogas /year (about 30 million m^3/day). India plans to install 110,000 biogas plants from 2014 to 2019. So far, the installed electricity capacity of biogas plants reached 179 MW in 2015 and 187 MW in 2016 (NBMMP).

Nepal has one of the most successful biogas programmes, with more than 330,000 household biogas plants installed under the Biogas Support Program and providing fuel for cooking purposes (REN21 2016). In **Vietnam**, the **Biogas Program for the Animal Husbandry Sector of Vietnam** started in 2003 and aims at developing commercial biogas plants, which led to 125,000 plants constructed until 2013 and 183,000 biogas plants until 2015. A National Domestic Biogas and Manure Program has been initiated in 2006 for rural and off-grid areas of **Bangladesh**, that resulted in about 36,000 domestic digesters installed by 2015, mainly for generating cooking gas. It is estimated that about 500–600 commercial biogas units are currently operational in the country in medium- to large-sized animal farms and generate electricity. There is a plan to reach a target of 100,000 biogas plants by 2020 and to install at least 130 commercial biogas digester systems by 2017 with an average capacity of 50 kW. A lower number of domestic biogas plants have been installed in **Sri Lanka,** with 6,000 biogas units and **Pakistan** with a number of 4,000 biogas plants (Kapoor 2013, Bertsch and Marro 2015).

Large volumes of waste are available in **Africa**, but biogas production is still less developed than in other regions. Biogas digesters are being installed in several countries (**Burundi, Botswana, Burkina Faso, Cote d'Ivoire, Ethiopia, Ghana, Guinea, Lesotho, Kenya, Namibia, Nigeria, Rwanda, Senegal, South Africa, Uganda and Zimbabwe**) (Biogas for Better Life Business Plan). National programs in Africa are currently implemented in **Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin, and Burkina Faso** (Austin G. and Morris G. 2012). In Africa, a Biogas Partnership Programme (ABPP) is being supported by the Ministry of Foreign Affairs of the Netherlands and Netherlands Development Organisation. This programme aimed at developing national biogas programmes in five African countries (**Ethiopia, Kenya, Tanzania, Uganda and Burkina Faso**) for building 100,000 domestic biogas plants to provide access to energy for a half a million people by 2017. The programme has led to the installation of almost 16000 biogas plans in the five countries (16,419 in **Kenya**, 13,584 in **Ethiopia**, 13,037 in **Tanzania**, 6,504 in **Uganda** and 7,518 in **Burkina Faso**) (Anon 2017). The African "**Biogas for Better Life**" initiative aims to provide two million household biogas digesters by 2020 to substitute traditional cooking fuels (wood fuel and charcoal) and provide clean energy for cooking for at 10 million people (van Nes, W. J. and Nhete 2007).

In Latin America, some agricultural biogas plants and several domestic biogas plants have been set up for rural households and biogas has also being extracted from several landfills. The **Network for Biodigesters in Latin America and the Caribbean** (RedBioLAC) promotes the development of small bio-digesters in **Bolivia**, **Costa Rica**, **Ecuador**, **Mexico**, **Nicaragua** and **Peru**. **Bolivia** is the leader with over 1000 domestic biogas plants installed. Large-scale biogas plants have been built to use effluents from palm oil mills and large agricultural operations in **Colombia**, **Honduras** and **Argentina**. **Brazil** had 127 biogas plants using agricultural and industry residues, biowaste, sewage sludge, and landfill gas recovery which produced about 1.6 million Nm^3/day, (584 billion m^3 biogas/year) representing 3,835 GWh of energy in 2015. The installed electricity capacity of biogas plants has increased significantly in the last years, reaching 196 MW in 2015 and 450 MW in 2016 (Kapoor 2013, Vögeli 2013, IEA 2017, Murphy 2017).

In the **United States,** there were more than 2,100 biogas plants, of which 247 farm-based digestion plants using livestock manure, 654 biogas recovery plants from landfill sites (US EPA Landfill Methane Outreach Program (LMOP)). From a number of 15,000 Waste Water Treatment Plants (WWTPs) in the United States, there were about 1,240 WWTPs operating anaerobic digesters producing biogas. Most of the on-farm AD plants in the country generated electricity (981 GWh in 2015) to meet the farm needs, and to supply electricity to the grid. The installed biogas electricity capacity reached 2400 MW in 2015 and 2438 MW in 2016. Almost all of wastewater biogas plants are installed at large scale facilities, treating from one to hundreds of millions of gallons per day of wastewater (US EPA 2017).

In Denmark, **Lemvig Biogas** has been the largest thermophilic biogas plant since 1992. Slurry from 75 farms and various wastes are co-digested to produce biogas for heat and power. The plant co-digests cattle and pig manure and slurries with biowaste (fish waste, household waste, slaughterhouse waste, soft drinks, alcohol, pharmaceutical waste). The plant processes yearly about 226,000 tonnes of biomass, consisting of 183,000 tonnes of manure and slurries and 43,000 tonnes industrial waste. The produced biogas it converted into electricity and heat using an Jenbacher 316 gas-engine (836 kW electricity, 968 kW heat). In 2013, a new Caterpillar engine (1560 kW) was installed. More than 21 million kWh of electricity is generated every year. The surplus heat from the gas engine cooling that exceeds 18 million kWh is sold to households.

Sønderjysk Biogas Plant Bevtoft (installed in 2016 with € 33 million investment) can co-digest over 600,000 tons of biomass yearly and has a capacity of 21 million Nm^3 of biomethane per year. The feedstock used includes farm slurry, straw and organic waste from the industrial sector. The AD process takes place in two steps. The first step is thermophilic, at 52 °C, and the second step is mesophilic, at 35 °C. The produced biogas is upgraded to biomethane through an amine scrubber chemical absorbtion process (Puregas Solutions biogas upgrading process). The selective organic solvents used are highly efficient, resulting in an end product containing more than 99 % methane.

In **Australia**, covered anaerobic ponds are the most common digester technology used to capture manure methane at Australian piggeries. Located near Young in New South Wales, **Blantyre Farms**, with approximately 22,000 pigs, was the first piggery in Australia to install a commercial-scale system to generate power from methane from an anaerobic (covered pond) system. The ponds are covered with a high density polyethylene (HDPE) cover. Biogas is used to produce electricity. To recover and use waste heat, biogas-fired engines at Australian piggeries are commonly fitted with heat exchangers. The waste heat is then recovered in the form of water at 70–80˚C, which is used for heating. Future development may involve the upgrading biogas to biomethane and use it excess for vehicle fuel use. Natural gas grids are not typically located in close vicinity to Australian piggeries. There has also been increasing interest to combine waste streams from a range of industry sectors, but relatively large distances between farms and fragmented supply chains are important barriers for development.

In **Brazil**, ITAIPU Binacional and the International Center on Renewable Energies – Biogás / CIBiogás have established a partnership to develop a demonstration biogas plant to digest grass cuttings, food waste and sewage effluent generated at the Itaipu Binational complex. The residues digested include: 15 t per month of food waste; 30 t per month of grass; 300 m^3 per month of sewage to produce 9000 m^3 of biomethane per month. The biogas is refined to biomethane with a patented process developed in Brazil, that integrates water scrubbing and pressure swing adsorption. The biomethane produced is supplied to over 60 ITAIPU Binacional vehicles. The demonstration is intended to allow replication across Brazil and to facilitate the development of a large number of urban residue biomethane facilities.

The waste treatment company **Attero** in the **Netherlands**, operates a green gas hub at Wijste that collects local biogas, combining the refining and injection steps for a number of digesters. Organic household refuse is separated from the grey waste stream and is digested separately. The Wijster plant is equipped with three installations for refining biogas to natural gas quality: a Pressure Swing Absorbtion (PSA) system; a water scrubber; and a membrane installation that, in addition to green gas, produces pure liquid CO_2 for the use in horticulture. A fourth installation at

Wijster is used to refine biogas to bio-LNG, a pilot project run by the Iveco Schouten. The biogas is supplied to the cryogenic installation, which is used to produce green gas to fuel lorries.

The Omnis/CPFL **Biogas Project** is a R&D project in **Brazil that** generates biogas from sugarcane vinasse, a wastewater derived from ethanol production, in a low-rate lagoon-based UASB reactor with a design throughput of 40 m^3 per hour. This low-cost anaerobic reactor (investment $2 million) full-scale R&D facility aims to optimize the biochemical process and assess the quality of digestate for sugarcane cultivation. The facility is based on a 14,400 m^3 lagoon-based UASB reactor (3 cells), mesophilic; with about 3,200,000 m^3 biogas produced per year (533 m^3/h). Biogas is biologically desulfurized in a packed-bed tower and used as fuel in a 1.1 MWe CHP unit to produce electricity for export to the grid; digestate is used as a fertilizer.

Ringkøbing – Skjern Municipality in **Denmark** has adopted an energy supply plan aiming to make it self-sufficient with renewable energy by 2020. The biogas will be produced in 40-60 decentralised farm scale biogas plants, connected by a biogas pipeline to the municipal CHP plants. The biogas potential is estimated at 30 million Nm^3 methane from animal manure and slurry and 30 million Nm^3 methane from energy crops. The first stage of the project entailed the establishment of five decentralised biogas plants, all connected to Skjern District Heating Plant. The premises for implementing first stage have since changed to ensure better utilisation of the waste heat in the district heating system. A wood chip fired biomass boiler has also been installed.

Sweden is world leading both in terms of automotive use of compressed and liquefied biomethane. Since 2012, liquefied biogas (LBG) is produced at the **Lidköping Biogas** Plant using waste from the food industry, which is a fuel attractive for long-distance road haulage applications, having a higher energy density. Today, only the amine scrubbing technology and cryogenic upgrading have the potential to achieve high purity in one step. The LBG is produced by cryogenic technologies, such as reverse nitrogen Brayton cycle or mixed refrigerant cycle. Existing biomethane liquefaction plants are operating in Sweden, Norway, UK, The Netherlands, USA and Philippines.

The biogas digester of the company Biogas Zürich started operation in 2013, built on the former composting site close to the wastewater treatment plant **Werdhölzli, Zurich in Switzerland**. Zurich Werdhölzli is the biggest in Switzerland, composed of a mechanical, a biological, a chemical treatment and a filtration unit. The sludges from the mechanical (primary sludge) and biological treatment (secondary sludge) are subjected to AD to generate energy. The biogas plant uses thermophilic process (>52 °C) for biowaste from households, green wastes from landscape management and private companies (25 Million CHF investment). The plant produces 12,180 MWh per year biogas. The raw biogas from both plants (biowaste and sludge) is transported by pipeline to an upgrading station with a capacity of 1,400 Nm^3/h. By removal of trace gases, H_2S and CO_2, the biogas is transformed into biomethane which is injected into the natural gas grid.

3.5 Thermochemical processing

3.5.1 Biomass combustion

New techniques were created for measurements of key parameters to develop diagnostic techniques for combustion (**TUCLA**) in order to enhance the understanding of combustion phenomena. Computer simulation tools and numerical investigations of the burning were also developed to facilitate the analysis and design of improved combustion systems (**SYNGAS, VADEMECOM**) by means of experimental, theoretical, and numerical simulation approaches. Research focussed to analyse and model turbulent combustion phenomena (**MILESTONE, HPC4E, HYBURN**), to use new high performance computing techniques to run combustion simulations to design efficient furnaces, engines, etc.

Several projects focused to develop and demonstrate various concepts and approaches for energy recovery from various waste materials and other biomass feedstock and covered the supply chain (solid recovered fuels) (**ENERCORN**). The production of biochar and application to soil was tackled as a novel approach to establish a significant long-term sink for CO_2 (**BIOCHARISMA**). Some projects also focussed on developing residential boilers based on liquid fuels combustion (**BIOLIQUIDS-CHP**), the utilization of pyrolysis oil from biomass residues (**Residue2Heat**) and to integrate catalysts into wood stoves to improve the burning process and reduce emissions (**BIOCAT**). Some projects aimed to develop improved low-cost woodchips feeding system providing appropriate fuel blends for small-scale and medium size heating plants (**BIOCHIPFEEDING**).

Some projects focused their work to study of the combustion behaviour of biomass fuels, of the ash fusion behaviour (**Biofficiency, ASHMELT**). The issue of biomass and ash composition was addressed in several projects, investigating the melting ash behaviour to achieve a clear understanding of the complex release chemistry of alkali metals (**ASHMELT**), to identify mechanisms for deposit formation and the behaviour of aerosols from biomass and to developed simulation tools for aerosol and deposit formation. Several projects addressed the issues of the pollutant and particulate emissions (**BIOCAT, EU-UltraLowDust, BioMaxEff, CYCLOMB**) and focused to develop cost effective dry gas cleaning and particle removal systens based on ceramic catalytic active filter candles or variable-geometry design systems. Some projects also addressed the development of low emission small-scale biomass combustion, for a range of residential biomass heating applications and for high efficiency performance small scale biomass boilers (**EU-UltraLowDust, BioMaxEff**).

Co-firing process was tested to achieve higher shares of biomass through advanced co-firing techniques (**DEBCO**) to develop and demonstrate innovative approaches to efficient co-utilisation of low quality biomasses and Solid Recovered Fuels (**RECOMBIO**). Research also aimed to improve the performances of combustion power plants by increasing steam temperature and pressure in new ultra-supercritical power plants (**MACPLUS**). A project focussed on a power plant concept based on flexible high-efficiency air-firing and oxygen-firing of fossil fuels with biomass and carbon capture through demonstration tests at upgrade to commercial scale (**FLEXI BURN CFB**). Some projects worked to develop CHP systems with internal combustion engines or gas turbines to use a variety of bioliquids including pyrolysis oil or to burn hydrogen-rich fuels from coal or biowaste gasification (**BIOLIQUIDS-CHP, GREENEST**). Several projects worked to develop hybrid systems that combine biogas or hydrogen, with PV or concentrated solar or combining a micro gas turbine and a solid oxide fuel cell to use biogas (**HRC POWER, Bio-HyPP**).

Several projects focussed to demonstrate cost-effective and high efficiency large scale energy generation systems using medium-temperature (150-400 ºC) (**PITAGORAS**) and low-temperature (30-150 ºC) (**LOVE, PITAGORAS, ICARUS**) waste heat. Some projects aimed to develop small scale (1 to 50 kWe) (**DeReco, ICARUS, ORC-PLUS**) to large scale (such as 100 kWe ORC) waste heat recovery systems (**FOUNDENERGY**) and up to large scale district heating (750 kWe ORC) (**SUNSTORE 4**). These projects aimed to select the most suitable fluid, to develop with advanced guidance and control systems, and to achieve optimal integration of thermodynamic cycles in order to increase the electrical conversion efficiency with advanced guidance and control system (**TASIO,**

FOUNDENERGY). Fundamental research was carried out into thermodynamics and heat transfer to design and develop new heat exchangers and new anticorrosive materials (**UP-THERM**) and for the estimation of the thermophysical and transport properties of nanofluids (**NanoORC**). Some projects combined several renewable energy sources, such as solar energy, CO_2 heat pump and biomass in in new hybrid systems (**PITAGORAS, SUNSTORE 4, HRC POWER)** to produce electricity.

3.5.2 Biomass combustion: international projects

Biomass combustion is operational and provides over 90% of the energy generated from biomass. Biomass combustion can be integrated with existing infrastructure in comparison to other thermochemical conversion technologies that require further development to reach commercial operation (i.e. gasification, pyrolysis, hydrothermal liquefaction). Combustion still needs to be improved and optimised to become cost efficient in comparison to conventional fossil technologies.

The IEA Bioenergy Task 32 Biomass Combustion and Co-firing works on further expansion of the use of biomass combustion for heat and power generation, with special emphasis on small and medium scale CHP plants. The Task collects and analyses strategic, technical and non-technical information on biomass combustion and co-firing applications, in order to increase acceptance and performance in terms of environment, costs and reliability (IEA Bioenergy Task 32, 2018). IEA Bioenergy Task 32 is organised by formulating joint projects between participating members and industry. The country participation includes Austria, Belgium, Canada, Denmark, Germany, Ireland, Italy, Japan, Netherlands, Norway, South Africa, Sweden and Switzerland. The activities focus on: i) market introduction for expanding the use of biomass combustion at a short term; ii) optimisation of biomass combustion technology to remain competitive at a longer term.

The **IEA Bioenergy Task 36 Integrating Energy Recovery into Solid Waste Management** aims to facilitate exchange of information on technical and non-technical issues related to the integration of energy into waste management (IEA Bioenergy Task 36, 2018). The Task works in close collaboration with Task 37 (on anaerobic digestion) and 32 (on biomass combustion and co-firing) on relevant issues, such as end of waste protocols and life cycle assessment. Task 36 includes initiatives to promote market deployment for sustainable energy generation from biomass, to stimulate interaction between RD&D programmes, international organisations industry and decision makers. The participating countries in this Task are France, Germany, Italy and Sweden. Task 36 examines the technology and trends of waste for energy (gasification, small scale and waste derived fuels), economics of energy systems and commercial availability. Specific actions relate to the analysis of recent and future trends to convert solid waste into liquid fuels and other commodities, including waste feedstocks, technologies, applications and drivers (with Task 33). Another activity relates to the examination of the role that energy from waste has to play in a circular economy, including the recovery of materials and by-products from waste.

Programs for renewable energy in the **United States** in general include the Improved Energy Technology Loan program, the USDOE Loan Guarantee program, and Advanced Energy Research Project Grants. All three of these programs are for commercial or research projects that would either reduce air pollutants and GreenHouse Gases (GHG) or reduce the dependence on energy imports. The Environmental Protection Agency proposed in 2014 a Clean Power Plan under the Climate Action Plan. The **Bioenergy Technologies Office (BETO)** in the **United States** oversees a research, development, demonstration, and deployment (RDD&D) program that focusses on how to improve five technical elements of bioenergy to lead to greater use of bioenergy in the US. The program focuses R&D efforts on feedstock supply, conversion, and the improvement of power generation technologies.

In **India** distributed/decentralized renewable power projects using bioenergy, wind energy, hydro power and hybrid systems are being established to meet the energy demand of remote communities. The main objectives are: supporting RD&D to make such systems more reliable and cost-effective, demonstration, field testing, strengthening manufacturing base for off-grid renewable energy, addressing biomass heat and power and industrial waste to-energy projects;

biomass gasifiers for rural and industrial applications. The Ministry of New and Renewable Energy (MNRE) has initiated several programmes for the promotion of **biomass** technologies and biomass power & cogeneration for promoting technologies for optimal use of biomass for grid power generation. A total of 288 biomass power and cogeneration projects with a 2665 MW capacity have been installed, consisting of 130 biomass power projects with a 999 MW capacity and 158 bagasse cogeneration projects in sugar mills with a capacity of 1666 MW. In addition, around 30 biomass power projects aggregating to about 350 MW are under various stages of implementation. Around 70 cogeneration projects are under implementation with a capacity of 800 MW.

In India a **National Biomass Cookstoves Initiative (NBCI)** was launched by MNRE in 2009 to enhance the use of **improved biomass cookstoves** and to design and develop efficient, cost effective, durable and easy to use devices. The initiative stressed the setting up of state-of-the-art testing, certification and monitoring facilities and strengthening R&D programmes. The project **A New Initiative for Improved Cookstoves: Preparatory Activities for Launch** aimed to assess the status of various types of cookstoves and their suitability, to prepare an action plan for development and deployment of improved cookstoves. As a part of National Biomass Cookstoves Initiative, pilot projects were taken up for demonstration of community size cookstoves. As follow up to the National Biomass Cook Stove Initiative (NBCI), MNRE initiated a new proposal for promoting the development and deployment of Biomass Cookstoves during the 12th Plan Period.

3.5.3 Torrefaction

Several projects focussed on the development of a process for large-scale production of torrefied bioenergy carriers for the use in power plants, as an intermediate energy carrier and in chemical industry. involving co-firing experiments, addressing process development, optimisation and characterisation of torrefied biomass, having in view the development of new standards (**SECTOR**). The projects focussed on the development of torrefaction and densification technology for a broad biomass feedstock range including clean woody biomass, forestry residues or agro-residues (SECTOR, **SteamBio**).

A project investigated thermal carbonisation, and hydrothermal carbonisation to produce biochar (**EUROCHAR**). A project investigated the thermochemical conversion of sewage sludge into biochar and synthesis gas that is further used to generate electricity via a gas engine (**PYROCHAR**), transforming municipal sewage sludge into useful charcoal (or biochar) and synthetic gas (or syngas). A project aimed to demonstrate a mobile concept enabling efficient pre-treatment of agro-forestry residues with superheated steam processing at high temperatures, allowing economic recovery of chemicals (**SteamBio**). A project aimed to demonstrate scale up of torrefaction technology using wood waste feedstock, integrated in a large-scale, industrially functional steel mill (**Torero**). A project aims at demonstrating at large scale the use of low quality biomass feedstock to produce an intermediate product with a high calorific value and good transport, storage and usage characteristics (**TORR**).

3.5.4 Torrefaction: international projects

In 2013, **Topell Energy** delivered a total of 2,300 tons of black pellets for a large-scale co-firing test to the **Amer** power plant of RWE Essent in the **Netherlands** to produce green electricity. The co-milling and co-firing took place at a rate of up to 25%. Critical items addressed during the test were dust formation, milling properties and burner stability. The trials therefore confirmed that high quality 'biopellets' can be produced and co-fired at large commercial scale with no adverse effect on milling and burning (Blackwood 2018).

Blackwood's testing facility located at **Prodock** in the Port of Amsterdam is used for torrefaction test work for clients and for Blackwood's R&D programs. The test facility consists of a test reactor and a testing lab for standard lab analysis. The test facility is used for determining the suitability for torrefaction of specific types of feedstock, as well as getting input for feasibility and engineering studies. Many different types of biomass feedstock have been successfully tested. Besides all kinds of woody biomass, other types of tested feedstocks include: straw, PKS, EFB, coconut shells, cocoa shells, miscanthus, elephant grass and olive residues.

A Dutch paper mill operates a **CFB CHP Blackwood** installation, which uses paper mill residues and forest residues to produce electricity and steam for paper production. Due to the low fuel quality, natural gas was always used as a support fuel. The use of torchips (torrefied wood chips from forest residues), lead to an improvement of the overall fuel quality, the CFB could operate without the need for natural gas as support fuel. This has led to a significant cost reduction.

Topell demo plant Duiven, the Netherlands. To develop and show-case industrial scale torrefaction of biomass, Topell Energy built an industrial scale (7 tons/hr output) demo plant in Duiven in 2010. From 2011 until 2013 the plant has been improved, driving production volume and quality towards the design specifications while incorporating fundamental learning into the installation. In the second half of 2013 and important milestone was reached: the world's first industrial scale production of torrefied pellets. The plant has been operational until 2014.

Co-firing tests at Amer power plant. After the proof of concept of the demo plant in 2013, a large co-firing test was conducted in a consortium with RWE Essent, Vattenfall Nuon and GDF SUEZ at the 600 MWe Amer 9 power plant in Geertruidenberg, the Netherlands. In total approximately 2,500 tons of torrefied pellets were co-fired at different co-firing rates. The test proved that torrefied pellets are a superior biofuel compared to regular wood pellets. Torrefied biomass can replace coal without additional investments as needed for co-firing wood pellets. The co-firing test was sponsored by the TKI Biobased Economy.

Two co-firing tests with Blackwood pellets were conducted in 2015 and 2016, at the **Hanasaari** and **Salmisaari** power plants of Helen Oy in Helsinki, Finland with torrefied pellets, to produce green electricity and heat. The torrefied pellets were produced using the torrefaction technology of Blackwood Technology. During these tests up to 30% of coal was replaced by torrefied pellets, without the need for special biomass infrastructure. The tests proved that the higher calorific value, easier grindability and higher durability make Blackwood pellets the ideal coal replacement for existing coal fired power plants.

In **Canada, British Columbia Bioenergy Network** (BCBN) funded in 2014 $1 million to **Diacarbon Energy** to demonstrate its Torrefaction Bioreactor Technology. BCBN is an industry-led association that acts as a catalyst for deploying near-term bioenergy technologies and organizing research for the development and demonstration of sustainable bioenergy capability in BC. Diacarbon will produce a renewable and sustainable biocoal derived from wood residuals to displace coal used by Lafarge Canada's cement operations in British Columbia. This BCBN funding complements $1.1 million from Sustainable Development Technology Canada and $7.0 million from private investors. The project involves the establishment of a fully automated torrefaction facility that will process wood residuals and demonstrate the production of biomass-based solid fuels.

Torrefaction is also being developed in the **United States**. **Zilkha Biomass Selma** (ZBS) plant that started the use of pellets in 2015 in Selma, Alabama. This plant is the first full-scale commercial Black pellet facility in the world, with an annual production capacity of 275,000 metric tons supplying durable, water-resistant pellets to the bioenergy market. Feedstock is sourced from the low-value fiber of sawmills and sustainably managed forests in Alabama.

Andritz has built a 1 t/h Torrefaction Demo Plant in **Sønder Stenderup**, Denmark that incorporates biomass (wood chip) drying torrefaction, pelletizing. The project is partially funded by the Danish EUDP, (Energy Technology Development and Demonstration Programme). The Danish Technology Institute (DTI), and Drax and Dong are involved as part of the EUDP team. Energy Research Center of the Netherlands (ECN) is a consultant to Andritz on the design of the torrefaction technology to be involved in the commissioning and optimization of the demo plant. Table 5 presents a selection of of torrefaction plants worldwide showing the technology used, capacity and TRL level.

Table 5. Selection of torrefaction plants worldwide

Country	Developer	Technology	TRL	Capacity (tonnes/year)
Austria	Andritz	Rotary drum	TRL 6-7	8,000
Belgium	Torr-Coal B.V.	Rotary drum	TRL 9	30,000
Belgium	CMI NESA	Multiple hearth	TRL 6-7	Undefined
Canada	Airex	Cyclonic bed	TRL 6-7	16,000
Canada	Airex	Cyclonic bed	TRL 4-5	Undefined
Canada	Airex	Cyclonic bed	TRL 4-5	Undefined
Denmark	Andritz / ECN	Moving bed	TRL 6-7	10,000
Finland	Torrec	Moving bed	TRL 6-7	10,000
France	LMK Energy	Moving bed	TRL 6-7	20,000
France	CEA	Multiple hearth	TRL 1-3	Undefined
Indonesia	Hip Lik Green Energy	N/A	TRL 9	100,000
Ireland	Arigna Fuels	Screw reactor	TRL 9	20,000
Netherlands	Horizon Bioenergy	Oscillating belt conveyor	TRL 9	45,000
Netherlands	Topell Energy	Fluidised bed	TRL 9	60,000
Netherlands	Konza Renewable Fuels	Rotary drum	TRL 6-7	5,000
Spain	Grupo Lantec	Moving bed	TRL 6-7	20,000
Spain	CENER	Rotary drum	TRL 4-5	Undefined
Sweden	BioEndev	Screw reactor	TRL 6-7	16,000
UK	Clean Electricity Generation	Oscillating bed	TRL 9	30,000
UK	Rotawave	Microwave	TRL 1-3	Undefined
US	Solvay/New Biomass Energy	Screw reactor	TRL 9	80,000
US	Agri-Tech Producers LLC	Screw reactor	TRL 6-7	13,000
US	Earth Care Products	Rotary drum	TRL 6-7	20,000
US	Integro Earth Fuels, LLC	Multiple hearth	TRL 6-7	11,000
US	River Basin Energy	Fluidised bed	TRL 6-7	7,000
US	Teal Sales Inc	Rotary drum	TRL 9	20,000
US	Agri-Tech Producers LLC	Screw reactor	TRL 4-5	Undefined
US	Terra Green Energy	Multiple hearth	TRL 4-5	Undefined
US	Wyssmont	Multiple hearth	TRL 4-5	Undefined

Scale and status: Pilot scale: 50 kg/h - 500 kg/h; Demo scale: > 500 kg/h - 2 ton/h; Commercial scale: > 2ton/h).

Source: Cremers et al 2015, ETIP, 2018.

3.5.5 Pyrolysis

Much of the focus has been on developing pyrolysis process, scaling up reactor, improving pyrolysis oil quality impact on downstream processing focussing on one-step or two-step pyrolysis, catalytic and non-catalytic pyrolysis for the production of heat and/or power, biochemical and renewable fuels from pilot, pre-commercial to full scale operation. Several projects aimed to generate process data of pyrolysis oil production to produce bio-oil and biochar from biomass, to improve the understanding of fast pyrolysis mechanisms (**ENV-BIO**), to determine the best operating conditions, and to improve the process and design of pyrolysis reactors (**MICROFUEL, BIO-GO-For-Production, PYROCHEM**). Some projects addressed bio-oil cleaning and improving the quality of the bio-oil produced and the development of the integrated bio-oil reforming for heat/power, chemicals (hydrogen, carbon nanotubes, chemicals), synthetic fuels, and biocrude production (**BIOBOOST, BioEcoSIM, PYROCHEM**).

The utilization of fast pyrolysis bio-oil from various agricultural and forestry residue streams has been tested (**Residue2Heat**) for residential heating applications (20-200 kWth) to provide heat. Research also focussed (**BioEcoSIM**) on the valorisation of manure in non-catalytic pyrolysis to convert carbon in manure into syngas and to produce sustainable soil improving biochar (P-rich biochar). Another area of interest included the use of the resulting intermediate processing streams for the production of various biochemials (**Bio4Products**). A project focussed on the development of a mobile pre-commercial microwave fast pyrolysis prototype to process forest residue and wood waste to charcoal and bio-oil to be used in boilers, engines and gas turbines (**MICROFUEL**).

Integrated biomass pyrolysis with gasification, thermo-catalytic reforming, and hydro deoxygenation processes were investigated for heat and power and for production of fuels (**bioliq, BIOFUEL, PYROGAS, MICROFUEL, TO-SYN-FUEL**). Pyrolysis systems using various catalysts have been investigated (BIOFUEL) to improve the catalytic pyrolysis of biomass by the use of novel catalysts, with reduced costs, optimization of catalyst selectivity towards desirable high value products (**ECOCAT, BIOFUEL, FLEXI-PYROCAT**). A project (**BIO-GO-For-Production**) focussed on the development of modular, integrated processes for the production of fuels from bio-oils and biogas. Several projects aimed the construction and demonstration of full-scale pyrolysis oil plants to produce electricity, to process steam and pyrolysis oil, and to replace heavy fuel oil in power plants (**EMPYRO, CHP Biomass pyrolysis, Fast pyrolysis**).

3.5.6 Pyrolysis: international projects

Fortum, UPM and Valmet started working together since 2014 on a five-year project **LignoCat** (Lignocellulosic Fuels by Catalytic Pyrolysis) to develop and commercialize integrated catalytic pyrolysis technology to produce higher value bio liquids or biofuels from cellulosic feedstocks. The idea is to develop catalytic pyrolysis technology for upgrading bio-oil and commercialise the solution. The project LignoCat (lignocellulosic fuels by catalytic pyrolysis). The project is a follow-up of the consortium's earlier bio-oil project together with the VTT Technical Research Centre of Finland, commercialising integrated pyrolysis technology for production of sustainable bio-oil for replacement of heating oil in industrial use. The LignoCat project is funded by Tekes - the Finnish Funding Agency for Technology and Innovation.

The first of its kind industrial-scale bio-oil production plant has been commissioned in **Joensuu, Finland** in November 2013. The plant, which has been integrated with Fortum's Joensuu CHP plant, will annually produce 50,000 tons of pyrolysis oil bio-oil from wood-based fuels, in addition to electricity and district heat from 250 000 solid m3 per year (100 000 dry tonnes). Overall energy efficiency of the integrated system: 90%. This annual production corresponds to the heating needs of around 10,000 households. This bio-oil plant, integrated with an existing heat and power plant, is unique in the world. The investment cost €32 million of which subsidised €8 million by state.

Table 6 presents a selection of of pyrolyis plants worldwide showing the different technology used, main product and the TRL level, which shous the different level or development at different technology developers worldwide.

3.5.7 Hydrothermal processing

In the hydrothermal processing, focus has been on both hydrothermal carbonisation and hydrothermal liquefaction of a wide range of biomass streams and, in particular, to provide economically attractive and environmentally friendly alternatives to utilisation of wet biomass. A project (**NewCat4Bio**) focused on the preparation, characterization and application of (hydro)thermally stable, homogeneous, and porous metallosilicate catalysts to be used in hydrothermal processes. Some attempts aimed to recover carbon from waste (**NEWAPP, EUROCHAR, HTC4WASTE**) through hydrothermal carbonization for converting organic waste streams into carbon neutral biocoal and to obtain high-value carbon products.

A wide range of waste streams have been used: green waste, agricultural waste, municipal solid waste, food and food industry waste, and sewage sludge. The projects aimed to develop new knowledge about the characteristics and uses of HTC coal and identifying feasible uses. The projects aimed to demonstrate the economic and technological performances of HTC installations. New projects (**HyFlexFuel, Hydrofaction**) focussed on advancing and demonstrating hydrothermal liquefaction conversion from diverse biomass feedstocks, increasing process integration and product recovery. The activities targeted the better understanding of relation between feedstock and process conditions, product yield and quality, and the valorisation of residual process streams. Most of the projects targeted upscaling technology from pilot to demonstration plant scale. Few projects (**Waste-to-Fuel, bioCRACK**) focus to transform the wood, straw or urban waste through liquefaction into bio-oils that is then used for the production of energy or renewable fuels at higher, demo scale.

Table 6. Selection of R&D pyrolysis plants worldwide

Project	Country	Status	TRL	Output
CanmetENERGY	Canada	operational	TRL 1-3	bio-oil
ABRITech Quebec	Canada	under construction	TRL 6-7	bio-oil, other syngas
AgriTherm	Canada	commissioning	TRL 6-7	bio-oil, chemicals
Ensyn	Canada	operational	TRL 6-7	bio-oil, chemicals
Ensyn Renfrew	Canada	operational	TRL 8	bio-oil
Ensyn Quebec	Canada	under construction	TRL 8	gasoline fuels
UDT	Chile	operational	TRL 1-3	bio-oil, chemicals
University of Science Technology China	China	operational	TRL 4-5	bio-oil
VTT Ltd.	Finland	commissioning	TRL 4-5	bio-oil
Fortum Joensuu	Finland	operational	TRL 6-7	bio-oil
Valmet	Finland	operational	TRL 6-7	bio-oil
Fortum	Finland	operational	TRL 8	bio-oil
Fraunhofer UMSICHT	Germany	operational	TRL 1-3	bio-oil
Fraunhofer UMSICHT	Germany	commissioning	TRL 4-5	bio-oil
KIT bioliq	Germany	operational	TRL 6-7	bio-oil, other
Pytec	Germany	idle	TRL 4-5	bio-oil (150 kg/h)
BTG	Netherlands	operational	TRL 4-5	bio-oil
BTG EMPYRO	Netherlands	operational	TRL 8	bio-oil, steam, power
Alternative Energy Solutions	New Zealand	operational	TRL 4-5	bio-oil
SP ETC	Sweden	operational	TRL 4-5	bio-oil, chemicals
Carbon Trust Pyrolysis	UK	no status	TRL 4-5	bio-oil (30 t/y)
Envergent	US	idle	TRL 4-5	bio-oil
KiOR	US	idle	TRL 4-5	bio-oil
KiOR	US	idle	TRL 1-3	bio-oil
Iowa State University	US	operational	TRL 1-3	bio-oil chemicals
NREL	US	operational	TRL 1-3	bio-oil
University of Idaho	US	operational	TRL 1-3	bio-oil, other
Mainstream Engineering Co	US	under construction	TRL 4-5	bio-oil
Mississippi State University	US	operational	TRL 4-5	bio-oil
Renewable Oil International	US	operational	TRL 4-5	bio-oil
RTI International	US	operational	TRL 4-5	bio-oil
USDA-ARS-ERRC	US	operational	TRL 4-5	bio-oil, chemicals
Virgina Tech	US	idle	TRL 4-5	bio-oil

Source: IEA Task 34, 2018.

3.5.8 Hydrothermal processing: international projects

IEA Bioenergy 34 Direct Thermochemical Liquefaction focus on the hydrothermal liquefaction and the upgrading of bio-oil and bio-crude to hydrocarbon fuels through fast pyrolysis. The overall objective of the Task is to improve the implementation and success of direct thermochemical liquefaction of biomass for fuels and chemicals, to overcome the barriers to commercialization of fast pyrolysis for liquid fuel production. The purpose of the Task is to: i) provide support for commercialization through standards development; ii) to validate applicable analytical methods for product evaluation; iii) support techno-economic assessment of liquefaction technologies; iv) facilitate information exchange with stakeholders. Participating countries include: Canada, Finland, New Zealand, Germany, the Netherlands, Sweden, United Kingdom and United States. Pyrolysis comprises all steps from pre-treatment to bio-oil conversion into a marketable product as fuel, heat and/or power, chemicals and char by-product. The technology review may focus on the thermal conversion and applications steps, but implementation requires the complete process to be considered. Process components as well as the total process are included in the scope of activities, which cover optimization, alternatives, economics, and market assessment (IEA Task 34 2018).

The world's first of a kind wood-based renewable diesel biorefinery, **UPM Lappeenranta Biorefinery,** has started commercial production in Lappeenranta, Finland in January 2015. UPM Lappeenranta Biorefinery is based on a hydrotreatment process developed by UPM, and produces approximately 120 million litres of renewable UPM BioVerno diesel yearly. The UPM BioVerno diesel, drop-in hydrocarbon is produced out of crude tall oil, a residue of pulp production, in the UPM Lappeenranta Biorefinery. A big portion of the raw material come from UPM's own pulp mills in Finland. UPM has built a € 175 million biorefinery without any public investment grants.

In Canada the **National Research Council Canada** (NRC) HTL pilot unit is designed and custom fabricated for testing and demonstrating the technology, and is one of very few in Canada at this scale. Hydrothermal liquefaction of these bio-feedstocks offers an alternate pathway to produce bio-crude and liquid fuels from wet organic streams. The NRC seeks industrial and municipal collaborators to test and optimize the technology for various waste streams and develop sustainable solutions to valorize low value waste streams to renewable biofuels, energy, and chemicals. This is especially attractive for industries and municipalities that can make use of waste residues to which there is a disposal cost.

Table **3** provides a selection of hydrothermal liquefaction plants worldwide, the TRL level and the main product.

Table 7. Selection of R&D Hydrothermal Liquefaction plants worldwide

Project	Project name	Country	Type	Outputs
Licella	Commercial demo plant	Australia	TRL 6-7	bio-oil
Aurora Algae*	Demo	Australia	TRL 6-7	bio-oil
National Research Council		Canada	TRL 4-5	bio-oil (30 t/y)
Pond Biofuels		Canada	TRL 4-5	renewable diesel
Steeper Energy	Continuous Bench Scale	Denmark	TRL 4-5	bio-oil
Aarhus University	Center for Biorefining Technologies	Denmark	TRL 4-5	bio-oil
Seambiotic		Israel	TRL 4-5	diesel-type hydrocarbons
Preem Petroleum		Sweden	TRL 8	diesel-type hydrocarbons
Green Star Products		US	TRL 4-5	diesel-type hydrocarbons

* idle

Source: IEA Bioenergy Task 34, 2018b

3.5.9 Biomass gasification

The aspects of optimisation and improvement of biomass gasification process were addressed by several projects, as well as research on gas cleaning, upgrading, reforming process to obtain a clean syngas. They aimed at up-scaling and demonstration of various gasification technologies using updraft and downdraft (**RENEGAS, FlexiFuel-SOFC, FlexiFuel-CHX**), fixed-bed gasifiers (**HiEff-BioPower**), (circulating) fluidised-bed gasifiers (**UNIQUE, GAS BIOREF**), atmospheric or pressurised reactors, using air or steam gasification, from micro-scale (25 to 150 kW) (**FlexiFuel-SOFC, FlexiFuel-CHX**) to larger scale (1- 10 MWe) (**HiEff-BioPower**). Many projects addressed demonstration of fuel flexible gasification technologies and to combine the different components into an integrated system.

Research focus was on the development and demonstration of syngas cleaning technologies using both chemical and physical methods to the limits required for upgrading to syngas (**GREENSYNGAS**). This addressed the control of different gas contaminants, and high temperature gas cleaning for biomass gasification. Several projects aimed to develop, integrate and prove a hot gas cleaning system at biomass gasification, and the reliability and performance of hot gas cleaning systems (**UNIQUE, HiEff-BioPower**). Research also focussed on gas cleaning to remove tars, particulate matter and other contaminants at high temperature, to produce gas that is ultra clean and that can be used for electricity and heat generation (**RENEGAS, HiEff-BioPower, FlexiFuel-SOFC, FlexiFuel-CHX)**.

Several projects were set to demonstrate biomass gasification based on various concepts at full scale in several sites, with a capacity ranging from for small power ranges to large scale. In general, the operation of previous projects proved to be difficult and they were closed down (**CHRISGAS**). Various projects aimed to demonstrate the use of a range of feedstocks from urban and industrial waste (energy crops, solid recovered fuel, derived from MSW, sewage sludge, etc.) (**GAS BIOREF, PHENOLIVE**), including gas cleaning, and handling, preparation, and feeding issues associated. They also aimed at studying, developing and testing the integration of biomass gasification and biogas engines (**PYROGAS**), fuel cells (**FlexiFuel-SOFC**), gas turbines (**H2-IGCC**) or gas burners (**FlexiFuel-CHX**). A project (**Ambition**) aimed to develop the combination and integration of a thermo-chemical and a bio-chemical process route - pre-treatment, gasification, gas cleaning and conditioning and syngas fermentation. In situ high-temperature concentration sensors have been targeted to develop sensors to measure various properties of the gases (**GASPRO-BIO-WASTE**). The environmental risks of a series of inorganic components into the gas phase, char residue and condensate have been addressed (**INORGASS**). The aspects of biochars production and use as valuable product were investigated (**EUROCHAR, PYROGAS).**

3.5.10 Biomass gasification: international projects

The **IEA Bioenergy Task 33 Gasification of Biomass and Waste** monitors, reviews and exchanges information on biomass and waste gasification research, development, and demonstration to promote international cooperation among and industry. The Task 33 monitors the current status and identifies hurdles to further development, to eliminate technological barriers to thermal gasification of biomass and waste. Task 33 conducted information exchange, investigation of selected studies, promotion of coordinated RD&D among participating countries and industrial involvement. The Task provides a forum to discuss the technological advances and issues critical to scale-up, system integration, and commercial implementation. Participating countries: Austria, Denmark, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland and USA. The work programme includes the survey of the current global biomass RD&D programmes, commercial operations and market opportunities for biomass and waste gasification, and identification of the technical and non-technical barriers to commercialisation of the technology (IEA Task 33, 2018).

In the **United States**, research on biomass gasification is supported by DOE's Office of Energy Efficiency and Renewable Energy (EERE). EERE's Biomass Program aims to improve **gasification** processes of a a range of feedstocks (agricultural products or wastes, wood and other forest products). The goals of the Biomass Program are to promote the use of diverse, domestic and sustainable energy resources and to reduce carbon emissions from energy production. The program's focus in **gasification** is on improving the processes for producing syngas from agricultural residues (corn stover and wheat straw) and energy crops (poplar and switchgrass) for the eventual production of ethanol. The struggle in the United States, as in most places, has been to move the biomass gasification technology from demonstration to a large scale commercial facility. Many of the large facilities have been abandoned quickly after operation.

Enerkem (Pontotoc, Mississippi) planed to build and operate a 300 ton per day waste-to biofuels plant in Pontotoc, Mississippi, using 190,000 tons of unsorted municipal solid waste (MSW) per year. Enerkem has developed a gasification technology that transforms MSW, forest and agri residues into transportation fuels, high- value chemicals and electricity. The plant is designed to produce 10 million gallons per year of ethanol with plans for future expansion that would double the capacity. Enerkem's conversion technology has been tested at pilot plant scale since 2003. The technology is now being applied at Enerkem's first commercial plant in Westbury, Quebec, Canada. The process combines gasification and catalytic synthesis and involves heat, pressure, advanced chemistry and the use of proven catalyst technology.

LanzaTech's Freedom Pines facility in Soperton, GA is a **gasifier** with capacity of 20 kg/hr for the production of jet fuel and chemicals from syngas derived from a variety of feedstocks such as pine biomass and corn stover. LanzaTech has developed a novel technology that converts syngas generated from any biomass resource (e.g. forestry residues, municipal solid waste, organic industrial waste, or agricultural waste) as well as waste gas containing CO or CO_2 from industrial sources into a range of fuels and chemicals. LanzaTech has demonstrated the production of over 25 new products from gas fermentation, including fuel ethanol or platform chemicals such as 2,3-Butanediol to be catalytically converted to bio butadiene, used for production of rubber and nylon.

INEOS Bio Cellulosic Plant in Vero Beach, Florida raised $130 million to build and run the plant in Vero Beach, Florida. The INEOS Bio plant in Florida is designed to produce 8 million gallons of ethanol every year and 6 MW of electricity. In the fall of 2013 the plant had been finished and was put online. In January of 2015 the plant had to be shut for a period of time because it started producing a hydrogen cyanide (HCN). The INEOS Bio gasification process is a two-step, oxygen-blown technology based on gasification and pyrolysis and converts the prepared, dried biomass waste into a synthesis gas comprising carbon monoxide, hydrogen and CO_2 gases.

ThermoChem Recovery International (TRI) operates a four dry tons per day **TRI pilot plant in Durham**, North Carolina that uses a steam reforming technology. This plant has tested various feedstocks, including wood chips, saw dust, rice hulls, grape plant pruning, municipal solid waste, poultry litter etc. This plant converts this biomass to biofuels and biochemicals. The Durham plant has seen over 9,000 hours of the steam reforming technology, and over 4,500 hours of biofuels production. TRI has licensed its technology to **Fulcrum Bioenergy**, who is building a 10 million gallons per year biofuel commercial plant in **McCarran,** Nevada. The commercial operations are expected to start in the first quarter of 2020. Sierra will be the first commercial-scale plant in the United States converting municipal solid waste (MSW) to fuels.

GTI Plant in Des Plaines, Illinois Gas Technology Institute (GTI) has tested at the pilot plant in Des Plaines the Adritz-Carbona technology that produces hydrocarbon drop in fuels. Tests have just recently finished at this pilot plant. During their runs they used over 300,000 lbs. of biomass to produce biofuels. By scaling up this technology, they would be able to build a commercial plant producing 57 million gallons per year of gasoline. After these successful trials, Haldor Topsoe is now looking for buyers of their technology in order to build a commercial scale facility.

The biomass gasification plant in **Güssing**, which started operation in 2002, has a fuel capacity of 8 MW and an electrical output of about 2 MWel. The plant consists of a dual fluidized bed steam gasifier, a two-stage gas cleaning system, a heat utilization system and a gas engine. Wood chips are converted through gasification into a syngas. The gasification process has operated in Güssing since 2002 for a CHP plant that has been in operations for more than 10000 of hours. The product gas is delivered at ambient pressure, has a high content of methane, higher hydrocarbons and tars. After the first eight years, R&D at Güssing focused on gas conditioning and SNG synthesis.

DONG Energy has developed the **Dong Pyroneer Plant** based on the Pyroneer gasification technology based on circulation fluidised bed (CFB) that converts biomass to gas at relative low temperature. The Pyroneer technology is designed for difficult biomass and waste products with high content of ash and salt. The **B4C** (Biomass for Conversion) project was to demonstrate the Pyroneer gasifier in a 12-times up-scaled version by designing, constructing and operating a 6 MW demonstration plant at Asnaes Power Plant in **Kalundborg, Denmark**. The 6 MW gasification demonstration plant was built in 2011 to test and verify the fundamentals of the low temperature CFB gasification concept to advance toward a commercial scale gasifier (size >50 MW).

The **Birmingham Bio Power Plant at Tyseley**, Birmingham, is a 10.3 MW biomass gasification plant using gasification to generate electricity from recovered wood waste since 2016. The biomass power project is being developed by Carbonarius, a joint venture of O-Gen UK and Una Group formed in 2010 to develop waste timber gasification facilities. The plant will be developed with a £47.8m investment by the UK Green Investment Bank and Foresight Group. The plant will generate electricity by combusting the syngas generated from recovered wood through gasification which will create high-pressure steam to drive the turbine. The power plant will be supplied with 67,000 tonnes of recovered wood waste a year

A **flagship gasification facility in Hoddesdon**, Hertfordshire, UK, is expected to become operational in 2018. The gasification technology is being provided by Biomass Power Hoddesdon Limited based in Stafford. The £60 million advanced conversion treatment (ACT) plant, being developed by AssetGen Partners. Green Investment Bank (GIB) and its partner Foresight Group, invested £30 million into the project. The Hoddesdon ACT will have capacity to treat over 90,000 tonnes of RDF and will be capable of producing 10MW of power for the National Grid.

Lahti Energy's Kymijärvi II is a gasification demonstration plant, with a capacity of 160 MW. Kymijärvi II produces 300 GWh of electricity and 600 GWh of district heat. Waste-derived fuel is gasified in an atmospheric pressure CFB gasifier, the gas is cooled and cleaned, and the clean gas is then burned in the boiler. The fuel consists of shredded textiles, wood, paper, card and plastics, etc.. Since 1998, Lahti Energy has gained plenty of experience in the gasification technology and its use in energy production. The commercial operation of Kymijärvi II started on 21 May 2012. The total budget of the project was € 160 million.

Cortus Energy has built an integrated production plant in **Köping, Sweden**, to run tests for drying, pyrolysis and gasification of different biofuels in the scale of 500 kW. The project is an up scaling of previous pilot projects based on the patented WoodRoll® process. During 2015 the demonstration plant in Köping, Sweden, has been rebuilt and upgraded to a fully integrated process to operate a fully integrated WoodRoll® process from wet biomass into a clean and energy-rich syngas, in a continuous flow. Funding comes from the Swedish Energy Agency, Triple Steelix, Movexum and Cortus. The tests have been completed and the results shall be evaluated design of the first commercial WoodRoll® plant which will have a capacity of 6 MW syngas.

In 2016 **Cortus Energy**, Swedish, made a cooperation agreement with Kuni Umi Biomass (Forest Energy), Japan, to develop the Japanese market for small-scale biomass electricity production. Cortus Energy and Forest Energy have decided to build a first 2 MW biomass power plant using Cortus Energy's "WoodRoll" gasification technology. The first 2 MWe power plant based on Cortus Energy's 6 MW thermal gas power WoodRoll facility will provide the basis for future cooperation on similar 2 MW power plants which could be up to 25 projects over the next five years.

E.ON has demonstrated gasification through the **Värnamo** Plant (6 MWe, 9 MWheat). The test program was concluded 1999, including more than 8500 hours of testing and 3600 hours of operation in total in IGCC. The Industrial partners and Växjö Värnamo Biomass Gasification Centre have started a project to rebuild the gasification plant to produce a syngas from biomass. The rebuild of the plant was planned to be finished in 2012 to be followed by a two-year testing programme. E.ON Sverige planneda **Bio2G** project in Sweden to build a first of its kind plant, a reference plant for a 200 MW gas bio-SNG (1.6 TWh/year) 16-24 MWe and up to 60 MW heat of district heating based on thermal gasification (investment cost of € 450 million). The fuel demand was estimated at about one million tonnes wood chips from forest residues (345 MW biomass).

Karlsruhe Institute of Technology (KIT), Germany, has developed a novel scalable technology to produce methane from CO_2, CO and H_2 in the **DemoSNG (Demonstration Substitute Natural Gas)** project. From the products of biomass gasification, i.e. H_2, CO_2 and CO, the DemoSNG pilot plant produces methane and water by means of a nickel catalyst (SNG operation). If green power is available, it is used for electrolysis and the production of additional hydrogen. The DemoSNG plant was installed into a standard shipping container and is mobile. The plant will be integrated and tested in Köping, Sweden into the gas flows of a biomass gasification plant of wood residues. The honeycomb catalyst can be implemented in various plant sizes. KIC InnoEnergy initiated the DemoSNG (Demonstration Substitute Natural Gas) project in the amount of EUR 4.5 million.

In India the MNRE is promoting biomass **gasifier** based power plants for producing electricity using local biomass such as wood chips, rice husk, cotton stalks and other agro-residues in rural areas. The main components of the biomass gasifier programmes are: i) distributed/off-grid power for rural areas; ii) off-grid applications in rice mills and other industries; iii) grid connected projects up to 2 MW capacities. The focus of the programme is to meet the electrical and thermal needs of industries and provide electricity for villages for lighting, water pumping and micro-enterprises. Emphasis is also given for small biomass gasifier power plants up to 2 MW capacities grid connected. About 150 MW equivalent biomass gasifier systems have been set up for grid and off-grid projects. More than 300 rice mills and other industries are using gasifier systems for meeting their power and thermal applications and 70 systems are providing electricity to more than 230 villages. The focus of RD&D activities in India are to the manufacture of: biomass integrated gasification combined cycle systems, simulators for RE grid-interactive power stations, alternate fuels and hybrid systems. **Error! Reference source not found.** provides a selection of RTD gasification plants worldwide.

3.6 Algae for bioenergy

Several projects focussed on the understanding fundamentals of algae and gain fundamental knowledge on aerobic respiration, photosynthesis, and fermentation in organisms (**ALFF, BEAL**) to develop and optimize of low input and application-based microalgae culture systems (**ALGAE4A-B**), or studying the metabolism of novel microalgae in low temperature bioreactors (**MONSTAA**). Several projects aimed to improve algae strains and cultivation techniques (**GIAVAP, SUNBIOPATH**) to reduce algal biomass production costs, using selected strains or genetically engineered microalgae species to make them better suited to specific growth conditions for different biomaterials. The projects focussed to investigate the molecular basis for efficient light energy conversion into chemical energy (**SOLENALGAE**), to increase photoconversion efficiency, to achieve optimal growth of selected strains in photo-bioreactors, and to improve the biomass yield (**DOP-ECOS, SUNBIOPATH, SOLALGEN, ECO-LOGIC GREEN FARM**). Some projects aimed to develop improved photonic materials that can be used to maximise algal growth (**BIOMIC-FUEL**) and a modular, scalable and automated biofilm reactor to produce algal biomass (**ALGADISK**).

Various cultivation, harvesting and extraction techniques were tested with microalgae species (**OPERATION SWAT, HARVEST**). Microlgae harvesting technology, a critical challenge faced by algae cultivation, has been investigated, including flocculating agents, filtration and ultrasound. Several solutions have been investigated on the use of nanotechnologies for downstream processing, production and harvesting of microalgae (**CMHALGAE, VALUEMAG**). A project (**ALGAEMAX**) used acoustic standing waves for harvesting high-quality microalgae biomass from their water-based growth medium. Few projects aimed to develop and demonstrate the biorefining processes of the algal biomass into high value products, ingredients and by-products from microalgae (**ABACUS, ALGAECEUTICALS, MAGNIFICENT, SABANA**).

While the majority of projects focussed on the use of microalgae, few projects addressed the cultivation and use of **macroalgae** (**AT~SEA, BIOSEA, GENIALG, MacroFuels**). The projects focussed on full chain on the development and validation of innovative, competitive processes of brown, red and green macroalgae to produce high value products and biofuels (**ALGAE4A-B, BIOSEA, MacroFuels**). A project aimed to develop advanced technical textiles to demonstrate the technical and economical feasibility of open sea cultivation of macroalgae (**AT~SEA**). Anaerobic digestion to convert the biomass into biogas was considered (**ALGAENET, ALL-GAS, DOP-ECOS**). Carbon dioxide and the nutrients released during anaerobic conversion will be used for microalgae production. The research aimed to develop methods tools for reliable analysis and optimization of the design and operation of integrated microalgal / bacterial system (**DOP-ECOS, SUNBIOPATH, BIOFAT**).

Several projects focussed to develop, upgrade, and scale up production of microalgae using nutrients from wastewater treatment effluents, as well as to improve the wastewater treatment process that uses microalgae to remove nutrients (nitrogen, phosphorus and other materials) from wastewater effluents (**INDALG, IPHYC-H2020, SABANA**) and to integrate the microalgae cultivation into a full-scale wastewater treatment plant (**ALGAMATER**). The removal of micropollutants (pharmaceutical residues) by micro-algae cultivation has been also addressed (**PHARM AD**) combining biological nutrient removal (nitrogen) with AD. Large-scale cultivation, harvesting and extraction (**GIAVAP, BIOFAT**) techniques were tested to microalgae species, investigating the use of wastewater effluents and nutrients and CO_2 capture to stimulate algae growth (**ALGADISK, ALL-GAS**). A project addressed algae demonstration production plant using real flue gas emissions (**INTERCOME**).

3.7 Algae for bioenergy: international projects

In the United States, the Bioenergy Technologies Office's (BETO's) **Advanced Algal Systems Program** funds the research and development (R&D) of algae production, logistics, and conversion to **algal** biofuels and bioproducts. The funded projects address a range of topics, including algal biology; algal cultivation, harvest, and processing logistics; conversion technologies; analyses of high-value co-products, techno-economics, sustainability, and resource availability. Advanced Algal Systems R&D Programme focuses on demonstrating progress toward achieving high-yield, low-cost, sustainable algal biomass production and logistics systems. Algal feedstocks include concentrated algae biomass, fermentable substrates, extractable lipids, secreted metabolites (alcohols or others), or biocrude from hydrothermal liquefaction (HTL). Algal biomass includes micro- and macro-algae, as well as cyanobacteria. The Advanced Algal Systems performance goal is to increase the productivity of large-scale algae cultivation and pre-processing while maximizing efficiency of water, land, nutrient, and power use to supply a stable biofuel intermediate for conversion to advanced biofuels. The program aims to validate the potential for algae supply and logistics systems to produce 5,000 gallons of oil (or an equivalent biofuel intermediate) per acre of cultivation per year at the pre-pilot scale by 2022; this will achieve a modelled plant minimum selling price of $3.00/gasoline gallon equivalent of algal biofuel (US DOE 2017).

The Sapphire Energy Green Crude Farm, the world's first commercial demonstration algae-to-energy facility (Integrated Algal BioRefinery - IABR), was operating in Columbus, New Mexico. Sapphire Energy was awarded $50 million grant from DOE for a demonstration-scale project to construct and operate a 120 ha algae cultivation farm and conversion facility to produce renewable bio-crude. Green Crude Farm integrated the entire value chain of algae-based crude oil production, from cultivation, to harvest, to extraction of green crude. The target capacity of this plant is 1 million gallons per year. (Laurens et al. 2017).

Muradel developed in 2014 an integrated demonstration plant to convert algae into green crude in Whyalla, **Australia**. The $10.7 million plant will produce 30,000 litres per year. This is a first step toward an 80 million litres per year commercial scale plant. The Murdel's technology, Green2Black, uses microalgae produced on site, plant biomass, and organic waste in an energy-efficient subcritical water reactor that converts the feedstock to crude oil. The demonstration plant was partially funded through a $4.4 million grant from Australian Renewable Energy Agency. The plant is the first of its kind in Australia.

Solazyme (now TerraVia) was awarded $22 million grant from DOE for an integrated biorefinery pilot project (demonstration of commercial production) in Riverside, Pennsylvania, involving heterotrophic algae that can convert cellulosic sugars into fuels and other products in a dark environment. This demonstration plant has a capacity to process daily 13 metric tons of dry lignocellulosic feedstocks, including switchgrass, corn stover, wheat straw, and municipal green waste, to produce to produce 300,000 gal yr-1 of purified algal oil, which can then be converted into FAME biodiesel or renewable (hydrocarbon) diesel. In 2016, Solyzme rebranded itself as TerraVia, shifting its focus to food and personal care products (Laurens et al. 2017).

In the United States, Algenol (Fort Meyers, Florida), was awarded $25 million from DOE for an integrated pilot project for algal conversion to ethanol (direct-to-ethanol process) and the delivery of a photobioreactor system that can be economically scaled-up to commercial production. Algenol has developed a platform for converting CO_2 to fuels (ethanol, gasoline, diesel or jet fuel) at lower cost and higher efficiency (one tonne of CO_2 to 144 gallons of fuel / 8,000 gallons per acre per year). Algenol uses fully closed and sealed photobioreactors utilizing industrial CO_2 emissions to produce transportation fuels enhanced algae using hydrothermal liquefaction and other conversion technologies. Algenol Technology is being demonstrated in **India** since 2015 together with Reliance Industries at Algae Fuels Demonstration Project located near the **Reliance Jamnagar Refinery**. Algenol's first commercial facility will include phased deployments of photobioreactors on an initial site of up to 2,000 acres, located on marginal land with access to salt water and CO_2 source.

In the United States, **Global Algae Innovations** (El Cajon, California) aim to increase algal biomass yield by deploying an innovative system to absorb CO_2 from flue gas using immobilized carbonic anhydrase, Kauai, HI, 33-acre algae facility ($1 million). **Arizona State University (Mesa, Arizona)** develops an atmospheric CO_2 capture, enrichment, and delivery to increase biomass productivity. Demonstrate that Moisture-Swing Sorption (MSS) can capture and concentrate atmospheric CO_2 ($1 million). **Pacific Northwest National Laboratory** (Richland, Washington) develops a process to produce microalgae directly from CO_2 in air, decoupling algal growth from CO_2 sources. It aims to develop and demonstrate AlgaeAirFix™, a novel process that overcomes current limitations of air-CO_2 supply to microalgae cultures ($900k).

In Canada the Algal Carbon Conversion (ACC) **Flagship program** in Canada promotes algae production, the conversion of CO_2 emissions into algal biomass, renewable biofuels and other value-added products through integrated algal biorefineries. The ACC program addresses the scaling-up algae cultivation technologies connected to industrial CO2 emitters, identifying the most appropriate algae strains for industrial deployment, increasing the productivity and reducing energy costs of photobioreactors, identifying ways to reduce energy required for processing algal biomass and assisting in the development of high-value, sustainable products from algal biomass.

In **Italy**, a pilot plant for CO_2 biofixation is underway near the Eni Oil Centre in **Ragusa**, producing green diesel. A strain of algae uses CO_2 separated from the gas and solar energy to produce a bio-oil for green refinery. The light collected is conducted by the optical fibres inside 14 photo-bioreactors. The facility in **Ragusa** is been developed by Eni based on technology patented by Sun Algae Technology in co-operation with Eni's subsidiary Enimed and *Compagnia per l'Energia Rinnovabile* in Ragusa. Eni has been carrying out a microalgae demonstration project within its refinery in Gela (Sicily) with ponds area of around 1 ha using algal species that are capable of growing on flue gases and waster streams from the wastewater treatment plant of the refinery. The expected lipid yields are 15-29 ton/ha/y.

EnAlgae project was a strategic Initiative of the INTERREG IVB North West Europe programme developing technologies for algae production. Three of the EnAlgae pilot facilities were dedicated to **macroalgae** (seaweeds) cultivation,, harvesting and conversion into bioenergy, at National University of Ireland, Galway, Queen's University Belfast (United Kingdom) and Centre d'Etude et de Valorisation des Algues (France). The aim was to evaluate offshore macroalgae cultivation methods, to develop and exchange best practice methods for the use of seaweeds . Six of the EnAlgae pilot facilities were dedicated **microalgae** cultivation, harvesting and conversion into bioenergy at Swansea University (United Kingdom), Hochschule Für Technik und Wirtschaft des Saarlandes (Germany), Ghent University, Wageningen UR/ACRRES (Netherlands), Plymouth Marine

Laboratory (United Kingdom). The activities aimed to explore ways to grow, harvest and use microalgal biomass in various conditions: microalgal photobioreactors or open ponds, using wastewater streams or CO_2 from anaerobic digesters or from gas turbine power production.

3.8 Biorefineries

Several projects targeted the development of a bio-economy concepts addressing diversity of processes, feedstocks and expected intermediate carriers and final products. Some projects focussed on advancing theoretical and experimental knowledge on reaction mechanisms, reaction engineering of the processing steps (**VALOR-PLUS**, **LIGNINFIRST**) processes integration, and integration of chemical and biochemical routes into biorefining (**IProPBio**). A project targeted the establishment of a coherent, well-coordinated and favourable regulatory / standardization framework for supporting the development of a cutting edge bio-economy and the standardization process for the concrete development of new value chains based on lignocellulosic feedstocks (**STAR4BBI).**

Some projects aimed to develop advanced biorefinery schemes to integrate biomass-processing sectors (biofuels, conventional fuels, power, pulp and paper, the food and agricultural industries) with conventional oil refineries (**BIOREF-INTEG, SUSTOIL**). Several projects aimed to develop technology and conceptual designs of biorefineries for the synthesis of bio-products, chemicals and/or materials together with the production of energy carriers, combining biochemical and thermochemical pathways. The projects aimed to create and demonstrate biorefinery concepts that can use various and multiple feedstocks and also closed loop integrated biorefineries and demonstrated the production of several products using various biochemical and thermochemical processes (**BIOCORE, VALOR-PLUS, EUROBIOREF**). A number of biological/ biochemical processes were investigated (**PROPANERGY, GLYFINERY, VALOWASTE, SYNPOL, FALCON, US4GREENCHEM, EnzOx2, LIGNOFLAG US4GREENCHEM**), thermochemical (**4REFINERY**) or the integration of hybrid bio-thermochemical process (**BioCatPolymers, TASAB**).

Various projects focussed to develop advanced biorefinery schemes to convert whole oil crops (**SUSTOIL**) and non-edible feedstocks (**EUROBIOREF, AFORE**) using multiple biochemical and thermochemical processes into energy (fuels, power and heat), food and bioproducts (chemicals and/or materials). The development of integrated biorefinery using algae was considered to produce valuable specialties and compounds from microalgae for application in food, aquafeeds and non-food products integrating a range of processing technologies (**D-FACTORY, MIRACLES, TASAB**). Another project addressed the concept of the cascading marine macroalgal biorefinery (**MACRO CASCADE**) for the generation of a diversity added-value products.

Several projects focussed to develop advanced and competitive biorefinery concepts using organic waste streams in order to produce various compounds (**AFORE, RES URBIS, VALOWASTE, VALOR-PLUS**), chemical building blocks, biopolymers or additives (**BioCatPolymers, SYNPOL, PROPANERGY, URBIOFIN**), and value-added fine chemicals (**SUBICAT, SUPRA-BIO**). Bio-based solutions were also investigated to isolate and upgrade natural chemicals from forest residues or process side-streams to be used for novel value-added applications (**AFORE, EUROBIOREF**). Several projects focussed to improve the biorefineries processes and upscalling to flagship plants (**AgriChemWhey, Exilva, PEFerence**) and demonstrate in first of a kind commercial scale flagship plant (**BIOSKOH, LIGNOFLAG**).

3.9 Biorefineries: international projects

The goal of the **IEA Bioenergy Task 42 Biorefining in a future BioEconomy** is to contribute to the development and deployment of integrated biorefinery systems and technologies as part of sustainable value chains (co-)producing food/feed ingredients, chemicals, materials, fuels, power and/or heat. The participating countries are Australia, Austria, Canada, Denmark, Germany, Ireland, Italy, The Netherlands and the United States. The work programme will include: analysis and assessment of biorefining in the whole value chain; biobased products/bioenergy standardisation, certification and policy activities at national, European and global levels; Analysing and advising on perspectives biorefining in a Circular BioEconomy. The main activities will consist in: international and national networking activities; standardisation and certification of biobased products; policy advice; the role of industrial and SME stakeholders from the bioenergy and biofuel sectors in the transition to a BioEconomy, and increased co-operation with other IEA Collaboration Programmes (i.e. IEA-IETS), IEA Bioenergy Tasks, and international organisations (FAO, OECD, EU ETIP and EERA Bioenergy, etc.) (IEA Task 42, 2016).

Bioenergy Technologies Office (BETO) in the **United States** addresses the integrated biorefineries and distribution infrastructure, RD&D tasks concentrating on demonstrating the reliability and success of biomass conversion technologies. These tasks focus on taking bench scale technology and developing it into pilot, demonstration, and commercial scale plants. The BETO's main role is to provide financial assistance. The US Department of Agriculture (USDA) has multiple programs to encourage industry to either build new biomass refineries or convert existing fossil fuel refineries. The USDA's **Biorefinery Assistance Program** is a loan guarantee program that assists in the development, construction, and retrofitting of commercial-scale biorefineries. The USDA Repowering Assistance Biorefinery Program is more specifically for providing incentives to retrofit existing power plants. The program can provide up to 50% of the cost to convert biorefineries from fossil fuel systems to biomass fuel systems.

The Energy Department (DOE) has selected six projects for up to $12.9 million in funding, entitled, "Project Definition for Pilot and Demonstration-Scale Manufacturing of Biofuels, Bioproducts, and Biopower." These projects will focuss on the manufacturing of advanced or cellulosic biofuels, bioproducts, refinery-compatible intermediates, and/or biopower in pilot or demonstration-scale integrated biorefinery. They will use thermochemical, biochemical, algal, and hybrid conversion technologies. The **AVAPCO** ($3.7 million) project will develop a demo-scale integrated biorefinery that combines AVAPCO's biomass-to-ethanol process with Byogy's alcohol-to-jet process to develop an integrated process that produces jet fuel from woody biomass. The demo facility will also produce renewable diesel and other bioproducts with another project partner, Genomatica. **LanzaTech, Inc. (Skokie, Illinois)** ($4 million) plans to design, construct, and operate an integrated demo-scale biorefinery that will use industrial waste gases to produce 3 million gallons per year of low-carbon jet and diesel fuels. **Global Algae Innovations (San Diego, California)** ($1.2 million) has developed novel technologies that improve several stages of the algae production process. This project seeks to design a pilot-scale algae biofuel facility with improved productivity of open pond cultivation and more energy-efficient algae harvest.

In 2017 DOE selected eight projects for up to $15 million DOE funding to optimize integrated biorefineries. These projects will work to solve critical research and developmental challenges for the scale-up and reliable operation of integrated biorefineries (IBRs), decrease capital and operating expenses, and focus on the manufacture of advanced/cellulosic biofuels and higher-value bioproducts. **TRI** (Baltimore, Maryland) will study and improve feedstock and residual solids handling systems targeted to commercial pyrolysis and gasification reactors. TRI's work will promote feedstock flexibility and enable the processing of low-cost feedstock to enhance economic viability. **Texas A&M Agrilife Research** (College Station, Texas) will work on a multi-stream integrated biorefinery (MIBR), where lignin-containing waste will be fractionated to produce lipid for biodiesel and quality carbon fiber. The MIBR will improve IBR sustainability and cost-effectiveness. **White Dog Labs** project (New Castle, Delaware) will use the residual cellulosic sugars in cellulosic stillage syrup to produce single-cell protein (SCP) for aquaculture feed. Currently, the syrup content is used for biogas production and as the solid fuel for boilers. The SCP is a higher-value product that could be generated from an existing stream and could enhance the economic feasibility of IBR. The **South Dakota School of Mines** (Rapid City, South Dakota) will demonstrate cost-effective production of biocarbon, carbon nanofibers, polylactic acid, and phenol from waste streams from the biochemical platform technology. These products will generate revenue for IBRs and help lower fuel cost. **NREL** (Golden, Colorado) will leverage and extend state-of-the-art modelling and simulation tools to develop integrated simulations for feed handling and reactor feeding systems. The simulation toolkit will be used to aid in optimizing biomass conversion processes and provide correlations to adjust optimal operating conditions based on feedstock parameters at Red Rock Biofuels' Biorefinery. **Clemson University** (Clemson, South Carolina) will develop analytical tools to identify an optimal IBR process design for reliable, cost-effective, sustainable, and continuous feeding of biomass feedstocks into a reactor for integrated process optimization for biochemical conversion. **Purdue** (West Lafayette, Indiana) aims to develop computational and empirical models detailing the multiphase flow of biomass materials. Purdue will characterize physical, structural, and compositional properties of biomass feedstocks, and compare the results with actual flow behaviour within a biorefinery. **Forest Concepts** (Auburn, Washington) proposes to develop feedstock handling modelling and simulation tools based on systematic analysis. The team will develop and validate a comprehensive computational model to predict mechanical and rheological behaviour of biomass flow for reliable design of handling systems.

In **Australia**, the Australian funding for clean energy is primarily federally based and comes under two key programs. Clean Energy Finance Corporation is an independent Government corporation that focuses on investment to secure investment in renewable energy, among others. It helps investment in developing bio-refineries in Australia. Australian Renewable Development Agency (ARENA) supports projects through early stage R&D to pre-commercial development (2012-2022). The Queensland Government in **Australia** is taking an approach for future development in 2016, the "Queensland **Bio-futures 10-year Roadmap and Action Plan**". The action plan envisages a $1 billion sustainable and export oriented industrial bio-technology and bio-products sector within 10 years. The Government envisages a wide range of products such as sustainable chemicals, fuels, cosmetics, detergents and textiles amongst others. Currently the largest operating commercial **bio-refineries in Australia** include Manildra, in NSW with a capacity of 260,000 liters of bioethanol per year using waste starch streams. The Sarina is located in Queensland, having a capacity of approximately 60,000 liters of bioethanol per year and uses molasses. The Dalby bio-refinery is located in Queensland with a capacity is approximately 85,000 liters per year and uses starch sorghum and a by-product is the protein enriched distiller grains.

The **SMIBIO** project addresses the technical-economic and environmental viability of small-scale integrated biorefineries, processing different kinds of biomass produced in rural and small urban areas, both in Europe and in CELAC (Community of Latin American and Caribbean States). Different (bio-)conversion processes (lignocellulosic biorefinery and AD biorefinery concepts) are integrated into a unique modular small-scale biorefinery concept which will be capable of transforming dry and wet biomass residues by means of different processes to produce a range of biomaterials and bio products maximizing the use of resources and energy efficiency. Four different rural/urban small-scale biorefineries (2 in EU and 2 in LAC countries) will be extensively studied, simulated and modelled under proper and real conditions. The best technical-economic integrated biorefinery to process the local biomass for each considered region shall be identified.

3.10 Other support programmes

NER 300 is a funding programme for innovative low-carbon energy demonstration projects having the goal to demonstrate and scale up Carbon Capture and Storage (CCS) and innovative renewable energy (RES) technologies at commercial scale (NER 300, 2018). NER 300 is funded from the sale of 300 million emission allowances from the New Entrants' Reserve (NER) set up for the third phase of the EU emissions trading system. The NER 300 programme planned to support various CCS technologies (pre-combustion, post-combustion, oxyfuel, and industrial applications) and RES technologies (bioenergy, concentrated solar power, photovoltaics, geothermal, wind, ocean, hydropower, and smart grids).

A number of 38 projects have been selected in 19 EU countries through two calls for proposals awarded in December 2012 and in July 2014. The cumulative NER 300 funding is €2.1 billion and about €2.7 billion of private investments. Eight projects on bioenergy were selected in the first call for proposals with a total funding of EUR 629 million. In the second call for proposals the six projects on bioenergy were awarded a total funding of €308 million. The projects cover bioenergy, concentrated solar power and geothermal power to wind power, ocean energy and distributed renewable management (smart grids). The EIB managed to raise only €2.1 billion. Four awarded NER 300 projects have been cancelled by the end of 2016, resulting in undisbursed NER 300 funds of at least €436 million. No CCS projects have been funded, and many large-scale bioenergy projects have failed to reach the final investment decision. Instead, the programme has funded a number of various smaller scale and technically less mature innovative renewable technologies.

In its proposal for a revised ETS for 2021–2030, the European Commission proposed a follow-up demonstration programme (SWD(2015) 135 final), the **Innovation Fund** (previously called the NER 400). The Innovation Fund was designed to enable highly innovative, low-carbon first-of-a-kind projects to support innovative low-carbon technologies and processes, especially in the demonstration phase. The Innovation Fund was endowed with 450 million emission allowances to support and demonstrate innovative technologies on carbon capture and storage, innovative renewable energy and low-carbon innovation in energy-intensive industry. The NER 300 and the Innovation Fund differ from the new European Fund for Strategic Investments. EFSI will work through financial instruments only, lending to existing projects ready to start within three years.

Supported by the European Institute of Innovation and Technology, **EIT Climate-KIC** is a European knowledge and innovation community, working to accelerate the transition to a zero-carbon economy. EIT Climate-KIC identifies and supports innovation that helps society mitigate and adapt to climate change. EIT Climate-KIC brings together partners from business, academia, and the public and non-profit sectors to create networks of expertise, through which innovative products, services and systems can be developed, brought to market and scaled-up for impact.

To reach the EU energy and climate objectives, further support is needed for innovative low-carbon technologies and processes in the demonstration phase, as a crucial step towards commercialisation and deployment. The **European Fund for Strategic Investments (EFSI)** is an initiative to help overcome the investment gap in the EU which aims to mobilise private investment in strategic projects. The Commission has identified the expansion of renewable energy R&D as priority areas of the EFSI. With EFSI support, the EIB Group (the European Investment Bank the European Investment Fund) and the Commission provide funding for economically viable projects, with a higher risk profile. It will focus on sectors of key importance. EFSI has a total of €33.5 billion (€26 billion guarantee from the EU budget, complemented by a €7.5 billion allocation of the EIB's own capital) and aims to unlock additional investment of at least €500bn by 2020.

EIB supports projects that make a significant contribution to sustainable growth and employment in Europe and beyond. Our activities focus on four priority areas, including climate and environment, supporting the transition to a low-carbon, environmental friendly and climate-resilient economy. EIB provides $100bn of climate-related projects in the five years from 2016 to 2020 to support COP21 Paris agreement climate goals. In 2017, the EIB financed €**16.7 billion in projects supporting and protecting the natural and human environment**. On sustainable, competitive and secure sources of energy, EIB provides financing on renewable energy: projects on solid biomass, wind farms, solar, hydropower and geothermal projects.

InnovFin – EU Finance for Innovators is a joint initiative launched by the European Investment Bank Group (EIB and EIF) in cooperation with the European Commission under Horizon 2020. InnovFin builds on the success of the former Risk-Sharing Finance Facility. **InnovFin Energy Demo Projects** (EDP) and Connecting Europe Facility (CEF) Debt tools are managed by the European Investment Bank. InnovFin has been designed to address the financing bottleneck identified in the EU's Strategic Energy Technology (SET) Plan. The InnovFin EDP instrument has already been amended using unspent NER 300 funds. InnovFin Energy Demonstration Projects enables the EIB to finance innovative first-of-a-kind demonstration projects at the pre-commercial stage that contribute to the energy transition, particularly in the fields of renewable energy technologies, smart energy systems, energy storage, and carbon capture utilisation and storage. Connecting Europe Facility (CEF) provides funding to the use of renewables in the transport sector. InnovFin financing tools cover a wide range of loans, guarantees and equity-type funding in the range of €7.5m – EUR 75m. EIB financing is limited to 50% of the total eligible costs of the project.

4 Impact assessment

4.1 Overview

The Energy Union Strategy (COM(2015) 80 final) has been build based on four interrelated dimensions designed to bring greater energy security, sustainability and competitiveness. This includes research, innovation and competitiveness for accelerating the decarbonisation of the European energy system cost-effectively. The Implementation Plan (IP) of Action 8, Bioenergy and Renewable Fuels for Sustainable Transport, proposed priority Research and Innovation (R&I) activities that need to be implemented in order to achieve the strategic targets adopted in the SET-Plan Declaration of Intent (DoI) agreed in 2017 by the representatives of the European Commission, SET Plan countries and stakeholders. The priority R&I activities are considered essential for achieving the SET Plan targets for renewable fuels, bioenergy and intermediate bioenergy carriers contained in the Declaration of Intent on Bioenergy and Renewable Fuels (2016) within the context of the EU Climate and Energy Package, the Energy Union and the Paris climate agreement. The Criteria for their selection include:

- support the development, demonstration and scale-up encompassing the entire TRL range;
- support efficiencies improvements and cost reductions versus the DoI targets;
- boost installing commercial capacity of renewable fuels for transport; and,
- comply with the timeline from now towards 2020 and 2030.

The R&I activities include the following for bioenergy and intermediate bioenergy carriers:

Bioenergy

- #8. Develop high efficiency large scale biomass cogeneration of heat and power;
- #9 Demonstrate high efficiency large scale biomass cogeneration of heat and power;
- #10 Scale-up high efficiency large scale biomass cogeneration of heat and power.

Intermediate Bioenergy Carriers

- #11 Develop solid, liquid and gaseous intermediate bioenergy carriers through biochemical / thermochemical/ chemical conversion from sustainable biomass;
- #12 Demonstrate solid, liquid and gaseous intermediate bioenergy carriers through biochemical / thermochemical/ chemical conversion from sustainable biomass;
- #13 Scale-up solid, liquid and gaseous intermediate bioenergy carriers through biochemical / thermochemical/ chemical conversion from sustainable biomass.

The analysis of the outcomes and goals of the EU projects and international research program and activities and global trends, discussed in previous sections, led to the following conclusions and specific recommendations for future priorities on research and development activities for each conversion technology of biomass to energy analysed in this report.

4.2 Cross-cutting bioenergy issues

A number of 91 projects have been identified as addressing general bioenergy issues, of which 6 projects under FP7, 46 projects under the IEE programme and 39 projects under H2020 RTD EU programmes. The **BIOTEAM** (IEE) aimed to assess the sustainability performance of a number of bio-energy pathways in six countries and check the relevance of alternative biomass pathways. The project developed a harmonized framework for assessing bio-energy pathways. National market system assessments (or 'market maps') were done for six countries for each bio-energy pathway. Strategic policy recommendations were issued on how to shape policy instrument packages.

The project **BioGrace-II** (IEE) contributed to harmonising calculations of GHG emissions for electricity and heat from biomass. It was a follow-up of the IEE-project BioGrace which harmonises GHG calculations for biofuels for transport. The BioGrace-II built an Excel-based GHG calculation tool for electricity and heat from biomass, together with a methodological background document, calculation rules and a user manual.

The mission of **BIOPROM** (IEE) was to identify and to overcome non-technical barriers for the implementation of bioenergy facilities in urban areas. The overall aims are the initiation of several bioenergy projects, communication of best-practice-examples, case studies and success factors, to stimulate a network and to accelerate the development of renewable energy technologies.

QUALITY WOOD (IEE) project aimed to increase the use of firewood by promoting better fuel quality management, to improve firewood production and supply chains and to promote the use of more efficient combustion appliances with less environmental impacts. It aims to disseminate information on firewood heating with higher efficiency and lower emissions as well as the technical level of firewood production and combustion equipment.

The **AFO** (IEE) project aimed to activate private forest owners to supply more woodfuel for increasing demand. Sub-regional wood supply clusters were established and developed in 5 regions (France, Slovenia, Latvia and UK), to improve the supply of wood. The project identified the challenges and the best solutions, e.g. practices, technologies and business models to overcome them and increase woodfuel supply by encouraging thinning and clearing in undermanaged forests.

The **AGRIFORENERGY 2** (IEE) project built on the previous project Agri for Energy and aimed to stimulate farmers to enter the European bioenergy market, specifically targeted improving communication between feedstock suppliers and energy producers. It enabled sharing of knowledge and experience to engender confidence in bioenergy developments. This was to increase the number of bioenergy investments and the capacity of bioenergy plant installed.

BASIS (IEE) aimed at interacting with bioenergy project developers and investors, providing them with a comprehensive view on the sustainable supply and competition for wood for wood chips boilers. BASIS produced a GIS tool to provide in-depth info on the regional supply and demand of wood chips, including on biomass potential, on current plants using wood chips (more than 4 000 plants larger than 1 MW identified), conversion efficiency, sustainability indicators and information on the logistic infrastructure. It produced a list of most existing bioenergy plants using wood chips.

Within the project **BEN** (IEE), a user-friendly regional energy planning tool was developed describing the real conditions, facilitates planning steps and supports decision-making. The biomass energy register visualises regional energy sinks and potentials of biomass. Local data was collected, standardised and transferred into a Geographical Information System (GIS). Based on this register, the local stakeholders developed regional masterplans for the sustainable use of biomass including guidance notes for management, technology and financing biomass investments.

BioEnerGIS (IEE) aimed at improving the sustainable energy exploitation of biomass at regional level developing a GIS-based decision support system which allows public decision makers and operators to identify the most suitable sites for biomass plants, in terms of energy, environmental and economic sustainability. The GIS-based DSS BIOPOLE combines supply and demand-side data, regional legislation, technological options and business plans to produce maps for capability localiszation. BioEnerGIS explored interest in realizing the plants, the different needs and the possible finance or laws instruments to encourage a shared action programme.

The objective of the **BIOENERGY FARM** (IEE) project was to increase the use and production of bioenergy and biofuels by farmers by providing information to farmers on the possibilities and feasibility of the available options. Such information was provided by the European Bioenergy Platform. Farmers are now able to do an online Bioenergy Quick Scan to assess the profitability and feasibility of bioenergy or biofuels for their farm. The experts have drafted several detailed business cases for projects that appeared to be feasible in order to support their implementation.

The **BIOEUPARKS** (IEE) project aimed at creating and promoting local biomass supply chains from sustainably managed forests and agri residues in nature parks. The project developed and tested a methodology for the design and management of biomass supply chains in protected areas based on short chains and small scale installations, respecting environmental and socio-economic sustainability. All five participating parks adopted a participatory approach where objectives and planning are shared with key local stakeholders in order to avoid and mitigate social conflicts.

BIO-HEAT (IEE) aimed to promote the use of Short Rotation Coppice (SRCs) as a source of energy for District Heating (DH) in Eastern European countries to set up new regional SRC to DH chains. Results and success stories transfer has been realized through training activities and the dissemination and promotion strategy. Specific training structures were developed for each of the target countries. Energy clusters to establish close collaboration between the biomass suppliers and the energy producers have been set up in all the participating countries.

The **BIOMASS FUTURES** (IEE) project aimed to quantify the sustainable role biomass can play to meet the targets for 2020 and to provide an understanding of bioenergy demand and supply and to what extend the production and use of domestic and imported biomass can contribute to EU27 energy needs. The project has been carried out to identify sustainable options for bioenergy development to 2030, and to increase awareness about the opportunities and the risks, and how these can be addressed. The project made market analysis and of biomass role, and spatial explicit biomass cost supply patterns, in different scenarios, timeframes and sustainability constraints.

BIOMASSPOLICIES (IEE) aimed to develop integrated policies for the mobilisation of resource efficient bioenergy value chains to contribute towards the 2020&2030 targets. The project produced guidelines for data collection to estimate and monitor sustainable biomass supply for selecting resource efficient value chains. It prepared an outlook of biomass value chains, updated cost-supply curves, a selection of promising feedstocks and a map of the feedstock-related policy landscapes . It produced benchmarking policy approaches for their market impact, resource efficiency, abatement of sustainability risks and competition and policy frameworks.

The **BIOMASSTRADECENTRES** (IEE) project aimed to create a more transparent market for wood fuels, and to mobilise the huge potential of biomasse. The consortium has edited a Wood Fuels Handbook and a Short Rotation Coppices Booklet. The consortium has edited the Guideline Biomass Logistic&Trade Centres-3 steps for a successful project. The BTC concept was recognised to be of strategic importance for the sustainable development of biomass sector, therefore measures for supporting the realization of BLTC were introduced in the Regional Rural Development Plan.

The **BiomasTradeCentre II** (IEE) project aims at increasing the production and the use of energy from wood biomass with realization of motivation events that will engage identified target groups to invest in production of energy from biomass. The aim of the BiomasTradeCentreII project is to transfer existing good practices in biomass production, biomass trade centres and energy contracting to all project partner countries. However, the main focus of the project is put on the quality assurance and quality control.

BioRegions (IEE) fostered the development of bioenergy regions at EU level building on the work of two most advanced areas by the creation of a comprehensive knowledge platform, which collected and evaluated positive and negative experiences. It also developed guidelines for using quality and sustainability criteria that ensure technological maturity of bioenergy ventures and positive development effects. The project helped to formulation of successful financing strategies (private and public funding) to define and implement Action Plans to get at least 1/3 of the energy demand from biomass, encourage and support other regions to replicate the activities.

CODE (IEE) focussed on industry-led assessment of the progress of the CHP Directive in the EU. The project aimed to raise awareness and provide information through information, know-how transfer among stakeholders to accelerate the market penetration of cogeneration technologies by producing a European Cogeneration Roadmap. The potential for cogeneration has been identified. CODE developed a tool for the assessment of support measures and barriers and a handbook with Best Practice Cases to conduct an analysis of the financial viability of cogeneration projects.

CODE2 (IEE) aimed to disseminate the lessons learned from the previous CODE project and will and helped structure and support the development of national and European CHP roadmaps. The guided roadmap approach and the lessons learned through developing roadmaps with the pilot Member States will be used for developing a concrete and realisable European Roadmap to 2030 as well as national cogeneration roadmaps for all Member States that provide improvement proposals in the areas of awareness, policy development and market opportunities.

CROSSBORDERBIOENERGY (IEE) aimed to help SMEs to evaluate bioenergy markets in view of cross-border investments on five bioenergy sectors: biogas, small scale heating, district heating, CHP and biofuels for transport. For each sector, criteria for market attractiveness have been identified. The market attractiveness has been assessed in relation to 50 criteria in 8 categories with 370 indicators. A GIS tool has been developed to visualise the market attractiveness.

EPIC2020 (IEE) aimed to promote the use of bioenergy potential of ports and surrounding areas. It assessed the bioenergy potential by identifying the links of biomass and bioenergy flows and creating know-how on the priorities, obstacles, potentials and best practices in port areas. It provided way to stimulate the establishment of bioenergy businesses by combining down-stream & up-stream approaches. EPIC2020 created implementation strategies by developing a vision a road-map for a symbiotic port development and a framework for public/private partnership agreements.

EUBIONET II (IEE) provided an outlook on the current and future biomass fuel market trends, by collecting feedback on the CEN 335 biofuel standards from market actors and analysing techno-economic potential of the biomass fuel volumes. The project aimed to analyse, select and describe the most suitable trading and business models for small and large scale biofuel supply chains for heat and power production by taking into account the environmental aspects and sustainability.

EUBIONET III (IEE) evaluated trade barriers and some solutions developed: the project contributed to the development of Combined Nomenclature codes for wood pellets, price indexes for wood pellets and wood chips and CEN standards for solid biofuels. Wood fuel price mechanisms were analysed, sustainability criteria for biomass were evaluated, new unexploited agro-industrial biomass sources were identified and case studies of biomass heating were prepared. An analysis of competition and prices of woody biomass use in forest industry and energy sector was carried out.

The objective of **FOREST** (IEE) was to work directly with businesses in the biomass supply chain, from farmers and foresters to architects and designers, to develop and consolidate long-term supply partnerships to increase end-user confidence and encourage greater investments in biomass heat. The project supported businesses through: 1. creation of a best practice tool-kit; 2. organisation of business-to-business networking events; 3. development of capacity building to pilot new supply chain models and partnerships.

The **MAKE-IT-BE** (IEE) project aimed at delivering agendas for bio-energy promotion in 4 EU Regions by developing and applying decision-making tools that assist in identifying, evaluating and initiating bio-energy chains. Bio-energy stakeholder platforms integrating bio-energy into regional energy programmes. The project delivered bio-energy agendas paving a way for the development of bio-energy chains addressing biomass supply&markets, bioenergy applications and technologies.

MIXBIOPELLS (IEE) aimed to support market implementation of biomass pellets by identifying the constraints and drivers and to find promising market concepts for enhancing the market relevance of alternative pellets for energy use. The project provided market information about alternative and mixed biomass pellets. A draft for a labelling system for alternative pellets and combustion systems was developed in close cooperation with the European Pellet Council considering possible utilisation concepts and the implementation in existing legal frameworks.

The **PELLCERT** (IEE) project assisted the development of standards and certification schemes for solid biomass. PellCert developed and implemented an EU certification system for pellets (ENPlus) to ensure uniform quality for wood pellets. It also addressed environmental aspects, and developed procedures for the sustainability of pellet production and trade. SolidStandards supported the implementation of EU standards for solid biofuels by delivering training, implementing standards in selected companies and collecting feedback on biomass standards from the stakeholders.

The objective of the **PromoBio** (IEE) project was to provide support to regional bioenergy initiatives and to facilitate new bioenergy business projects in Eastern European countries. Best bioenergy practices and successful business models were tested and transferred to the target regions. The aim is to provide the local stakeholders with the grounds to make informed decisions in developing the bioenergy markets of their region. The project provided concrete supporting actions to decision makers and companies starting or developing bioenergy business.

In the **SolidStandards** (IEE) project, solid biofuel industry players were informed and trained in the field of standards and certification to use their feedback to the related standardization committees and policy makers. A number of 35 training events were organised for producers and end-users of solid biofuels aiming at increasing the target groups' ability to implement quality and sustainability standardization and certification. The consortium worked with selected solid biofuel companies and to support them in implementing European quality standards.

SRCPLUS (IEE) supported the development of local supply chains of Short Rotation Crops (SRC) by implementing capacity building measures and regional mobilization actions in local supply chains. The project started with an analysis of sustainable SRC local supply chains and identification of best practises. The project promoted sustainable practices in the SRC supply chains in order to create and highlight especially the environmental benefits of SRC in comparison to other crops.

The main objective of **SUCELLOG** (IEE) was to increase the participation of the agri sector in the sustainable supply of solid biofuels. SUCELLOG supported the creation of solid biofuel logistic centres in the agro-industry evidencing the synergy existing between the agro-food economy and the bio-economy and covering the gap of knowledge of agro-food industries. Various facilities form agriculture can be used in the idle periods to handle and pre-treat feedstocks obtained from different sources (agri and forestry residues, landscape cleaning, etc.) into quality solid biofuels.

The **Woodheat Solutions** (WHS) (IEE) project contributed at boosting wood fuel use in England, Slovenia and Croatia by working with small scale woodland owners, farmers and heat users to raise awareness of the advantages of wood fuel for heat production, and to implement wood fuel supply and wood heat production projects. The project addresses the barriers of insufficient co-operation, information and training to mobilise the biomass potential from fragmented forests and agricultural land and integrate the two sectors into the energy market as a raw material or energy supplier.

BIOTRADE2020PLUS (IEE) provided guidelines for the development of a European Bioenergy Trade Strategy that ensures that imported biomass are sustainably sourced and used efficiently, while avoiding distortion of other markets. Technical, economical and sustainable potentials and sustainability risks of biomass and bioenergy carriers were assessed, with a focus on wood chips, pellets, torrefied biomass & pyrolysis oil from major sourcing regions. Technical evaluation of their production and distribution costs, market prices, actors and sustainability profiles was provided.

The aim of the **ENERCOM** (FP7) project was to demonstrate high-efficient polygeneration of electricity, heat, solid fuels and high-value compost/ fertilisers from sewage sludge and greenery waste mixed to biomass residues. The concept allows achieving high overall energy efficiency by the use of low temperature heat from the co-composting process and a highly efficient gasification process. The project aimed to set up a polygeneration demo plant on an existing compost facility, to recover minerals and nutrients from ash and remove heavy metals and harmful fractions.

The **BIOMOB** (FP7) project aimed to identify opportunities for commercialisation of applied research into biomass mobilisation. Regional challenges were addressed by profiling biomass resources in each region and identifying regional shortcomings between resources and research capabilities. BIOMOB formulated recommendations to expand local bioenergy systems and proposed technological and networking processes resulted from nine case studies.

BESTF (FP7) aimed to start large scale investment in close-to-market bioenergy, helping to achieve the objectives of the European Industrial Bioenergy Initiative (EIBI) Implementation Plan. BESTF implemented a collaborative funding call to support bioenergy projects. These projects had to demonstrate the performance and reliability of all critical steps in a value chain so that the first commercial unit can be designed and performance confirmed from the demo unit.

BESTF2 (FP7) has established a cooperative funding scheme to support close-to-market projects focused on the generation of bioenergy. BESTF2 provided financial support to innovative bioenergy demo projects to facilitate the transfer of applied research to market. Six projects have been selected for funding and received funding at three levels: national, EC and industry. The BESTF programme supported bioenergy demo projects addressing one of the seven EIBI bioenergy value chains, are at an proper stage of development and move into demo phase and are industry-led.

BRISK (FP7) aimed to encourage and facilitate cooperative research in thermochemical biomass conversion and granting researchers access to high-level experimental facilities. Another focus is on developing advanced measurement methods and procedures in thermochemical biomass conversion. Thermal gasification and upgrading technologies are being refined to improve flexibility of the gasifier. Another task is to improve methods for advanced testing and optimisation of catalytic processes of biosynthetic gas conversion into liquid or gaseous biofuels.

The main aim of **S2BIOM** (FP7) project was to support the sustainable delivery of non-food biomass feedstock through developing strategies and roadmaps. The project built up a knowledge base for the sustainable supply and logistics of biomass (amount, cost, technological pathway options), for the development of technology and market strategies to support the development of a resource efficient bioeconomy. This includes bio-based industries as well as energy conversion.

ADVANCEFUEL (H2020) aimed to facilitate the commercialisation of renewable transport fuels by providing stakeholders with new knowledge, tools, standards and recommendations to help remove barriers to their uptake. The project examined the challenges of biomass availability and how to improve supply chains. New and innovative conversion technologies were explored to see how they can be integrated into energy infrastructure. A decision support tools will be created for policy-makers to enable a value chain assessment, as well as scenarios and sensitivity analysis.

AGRIFORVALOR (H2020) plans to close the R&D divide by connecting practitioners from agriculture and forestry to research and academia, associations and clusters, bio-industry, policy makers; support organisations, innovation agencies and technology transfer liaisons in multi-actor innovation partnership networks. Research results and good practices on valorization of biomass sidestreams from agro and forest will be shared and matched with the specific needs, potentials and dedicated innovation support applied, to further deploy selected topics.

AGROinLOG (H2020) will evaluate the technical, environmental and economic feasibility of the Integrated Biomass Logistic Centres (IBLC) for food and non-food products. The project is based on three agro-industries in the fodder (Spain), olive oil production (Greece) and cereal processing (Sweden) sectors that are willing to deploy new business lines in their facilities to open new markets in bio-commodities (energy, transport and manufacturing purposes) and intermediate bio-products (transport and biochemicals).

The **Ambition** (H2020) project will develop a long-term joint European Community Research and Innovation Agenda on the integration of biofuels production and surplus electricity valorisation. AMBITION targets the challenge of system flexibility by integrating two energy carriers, e.g. electricity and biofuels. The project targets a set of aspects of the integration challenges in line with the priority areas of the SET plan Integrated Roadmap. AMBITION improves the material and energy efficiency of the conversion processes and reduces capital and operation costs.

Amicrex (H2020) plans to develop an integrated process design for future industrial implementation, where by-products from agro industrial processes (e.g. carrot peels) can be valorised by recovering high- value nonpolar components (e.g. carotenoids, well recognized natural pigments and widely used in the food and cosmetic industries) through a microwave intensified microemulsion extraction process.

This **BESTF3** ERA-NET Co-fund will bring together a number of national&transnational organisations for promoting greater use of bioenergy. It follows two previous BESTF ERA-NET Plus initiatives to kick-start large-scale investment to achieve the objectives of the European Industrial Bioenergy Initiative (EIBI) Implementation Plan and the Strategic Energy Technology (SET) Plan. BESTF3 will implement an integrated action to promote the development of bioenergy demonstrators and providing a financial support to projects that are close to commercialisation. BESTF ERA-NET will implement a joint programme for bioenergy demo projects to demonstrate bioenergy technologies, leveraging public-private partnerships to manage the risks.

BestRES (H2020) aims to identify best practices business models for renewable electricity generation in Europe taking into account new opportunities and synergies coming along with changing market designs in line with the EU target model. Business models investigated shall make use of the aggregation of various renewable sources, storage and flexible demand. The improved business models will be implemented during the project in real-life environments, depending on the market conditions, to proof the soundness of the developed concept.

Bioenergy4Business (H2020) supported and promoted the substitution of fossil fuels used for heating, by bioenergy sources (industrial waste, forest biomass, straw and other agri-biomass). Results of the project include information about market potentials, capacity building/training, decision-support tools and communication activities targeted at relevant stakeholder, tools to support the assessment, planning and implementation of such projects, dissemination of best-practice business models and of the information about best practice support measures and policies.

BioEnergyTrain (H2020) project addresses the creation of new post-graduate level curricula in key bioenergy disciplines, and a network of tertiary education institutions, research centres, and industry stakeholders. The project will foster European cooperation to provide a highly skilled and innovative workforce across the whole bioenergy value chain, closely following the recommendations of the SET-Plan Education Roadmap.

The overall goal of the **Biomasud Plus** (H2020) project is the improvement, dissemination and market development of the Biomasud label to promote the sustainable use of the Mediterranean solid biofuels in the domestic sector. A GIS tool providing information about biomass resources and costs was updated and upgraded with info about agro-industrial residues and pellets production and producers. Biomasud Plus will develop new and review the existing Biomasud label analytical limits and sustainability tools along the value chain, including the GHG calculation procedure.

BioRES (H2020) aimed to introduce an innovative concept of Biomass Logistic and Trade Centres (BLTCs) that will help increasing the demand for bioenergy (firewood, wood chips, wood pellets, and wood briquettes). BioRES identifies locations for new BLTCs, assesses regional potentials for the production and use of bioenergy, and initiates stakeholder dialogues involving producers and users of bioenergy. The innovative concept for BLTCs builds upon the results of previous and on-going EU programs, e.g. BIOMASS TRADE CENTER II, FOROPA, SolidStandards and BIOREGIONS.

Biovalue (H2020) project aims to build a novel biomass scanner for the measurement of biomass that will be based on its 1st generation solution for the pulp and paper industry. The new solution will analyse various types of biomass. Manex will build and test a full scale demonstrator at a trial customer and analyze the biomass on a moving conveyor belt in realtime determining the most important key parameters (i.e. moisture content, calorific value, ash content and unwanted items) to high precision. Accurate knowledge of biofuel quality will be available in real time.

The **BioVill** (H2020) project will develop regional bioenergy concepts in Slovenia, Serbia, Croatia, Macedonia and Romania up to the investment stage in order to become "bioenergy villages". This will increase the market uptake of bioenergy on the basis of cooperation with partners from countries with established bioenergy markets (Austria, Germany). The individual biomass value chains will include the production and distribution of heat and electricity. The concepts include technical and non-technical aspects for each target village.

BRISK II (H2020) aims to establish a centre of excellence in the field of 2nd and 3rd generation biofuels via the uniting of leading European research infrastructures. BRISK II Networking Activities will consolidate the knowledge in the field. Joint Research Activities will yield an improvement in the characterisation of feedstocks for thermochemical and biochemical conversion processes, at micro-scale and macro-scale. Enhanced techniques will lead to significant gains in process flexibility and reliability. New biorefining approaches are intended to explore novel process combinations.

DIABOLO (H2020) aims to strengthen the methodological framework towards more accurate, harmonised and timely forest information; enable the analysis of sustainable biomass supply derived from multipurpose and multisource national forest inventories; and facilitate near real-time forest disturbance monitoring. DIABOLO will make innovative use of existing field-collected data and EC space-based applications of EO and satellite positioning systems with reference to INSPIRE and GEOSS, and global monitoring systems such as REDD+, FLEGT and UNFF.

The objectives of this **EcoBioMass** (H2020) project are to optimize, demonstrate and commercialize the EcoBioMass system, an automated system for harvesting and processing small diameter trees. EcoBioMass automatically cuts tree stems into pre-specified lengths and bundles them together for forward transport. In relation to existing solutions, the system increases the efficiency of small diameter tree harvesting.

The goal of **ENABLING** (H2020) is spreading of best practices and innovation in the provision (production, pre-processing) of biomass for the bio-based industry. In particular, ENABLING aims at creating appropriate conditions for the development of efficient biomass to bio-based products and processes value chains. Upscaling biomass production and pre-processing would enhance three types of impact: a) meet higher demand in bioenergy and BBI; b) reinforce-ment of biomass supply for the BBI benefits smaller BBI players; c) job-creation from biomass and BBPs linkages.

ERIFORE (H2020) will establish open access bioeconomy research infrastructure enabling scientific discoveries to be transferred to new business models, novel products and services. ERIFORE will coordinate, complement and update major European research infrastructure to enable the full potential of forest biomass in balance with diverse uses. The research infrastructure will focus on topics supporting Circular Forest Bioeconomy concepts, including fundamental teaching, knowledge sharing to high level research labs and large scale piloting facilities.

ETIP Bioenergy-SABS (H2020) aims to support the contributions of biofuel and bioenergy stakeholders to the Strategic Energy Technology (SET)-Plan. The project will assist the European Biofuels Technology Platform (EBTP), to prepare the transition to a European Technology and Innovation Platform Bioenergy (ETIP Bioenergy). Key elements are to enable contribution to the SET-Plan activities and strategy on RES integration, technology cost reduction and upscaling; defining priorities, strategies, investment decisions and programmes; identification of technical and non-technical barriers; assistance in defining research programmes and financial instruments.

The objective of **FACCE SURPLUS** (H2020) is to strengthen the European Research Area in support of different integrated food and non-food biomass production and transformation systems, especially by organising, implementing and co-funding with the EU a joint call for transnational research projects on the topic of sustainable and resilient agriculture. This topic falls within the scope of the Strategic Research Agenda (SRA) of the Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE–JPI).

FORBIO (H2020) will demonstrate the viability of using land for non-food feedstock production without interfering with the production of food or feed, recreational and/or conservational purposes. FORBIO will develop a methodology to assess bioenergy production potential on available “underutilised lands” (contaminated, abandoned, fallow land, etc.). FORBIO will provide multiple feasibility studies in selected locations to set the basis for building up local bioenergy value chains that meet the highest sustainability standards and improve efficiency and sustainability.

The objective the **GRACE** (H2020) project is to demonstrate the upscaling of crop production of miscanthus and hemp genotypes matched to end use and their suitability for marginal, contaminated and unused land. Another aim of the project is to demonstrate the upscaling of promising biomass valorization chains with tailored genotypes. Valorization options were tested and demonstrated at precommercial scale including their performance and environmental and economic profile.

The aim of **greenGain** (H2020) is to strengthen the energy use of regional and local biomass from the maintenance of areas and landscape elements. The scope of the biomass used will be any material produced from nature conservation and landscape management, but not from energy-crops. The project will show strategies to build up reliable knowledge on local availability of these feedstocks and know-how on issues from logistics to storage and sustainable conversion pathways for the transformation of these feedstocks to renewable energy (heat and energy products).

InnoPellet (H2020) project aims to develop a self-supporting biofuel pellet producing system for treating communal sewage. Previous development led to the completion of a prototype. InnoPellet plans to commercialise the units and pelleting services to wastewater companies. The InnoPellet system offers an economical solution of sewage sludge treatment for wastewater companies. This technology is a self-supporting machinery for drying and pelleting sewage sludge without external need of fossil fuel or any other additional material.

MOBILE FLIP (H2020) aims at developing and demonstrating mobile processes for the treatment of underexploited agro and forest based biomass into products and intermediates. Process concepts have been designed around the key technologies: pelletizing, torrefaction, slow pyrolysis, hydrothermal pre-treatment and carbonisation. Four mobile process lines have been designed and are under way to be tested: hydrothermal pre-treatment, torrefaction, slow pyrolysis, pelletizing.

SecureChain (H2020) promotes the implementation of sustainable supply chain management practices in six EU regions to better integrate local SMEs into biomass supply, processing and bioenergy production. This aims to increase biomass mobilisation and reduce the transaction costs for market uptake of efficient systems. Complete LCA of pilot supply chains evaluates the environmental and socio-economic impacts; a risk assessment is carried out to several supply chains.

The aim of the **SEEMLA** (H2020) project is the reliable and sustainable exploitation of biomass from marginal lands (MagL), which are not used for food or feed production and are not posing an environmental threat. The aim of the project is to define MagL to develop and optimize cropping systems for special sites. The project will focus on three objectives: the promotion of re-conversion of MagLs for the production of bioenergy through the involvement of farmers and foresters, strengthening of local small scale supply chains and the promotion of plantations on MagLs.

The **SYSTEMIC** (H2020) project aims to turn biomass waste from AD value chains into valuable products while reducing water pollution, GHG emissions and creating jobs in rural areas. The demo plant will allow innovative combinations of modules to elaborate possible optimizations for increasing the production quantity and quality of new products. The SYSTEMIC industry-driven consortium will validate for the first time the technical and economic viability of a fully integrated, multistep approach in an operational environment.

uP_running (H2020) project aims to set the path for the development of the bioenergy utilisation of agrarian pruning and plantation removal (APPR) wood from vineyards, olive groves and fruit tree plantations. uP_running goal is the mobilisation value chain actors for the utilization of APPR woody biomass. For that purpose, uP_running incorporates a set of straight actions aimed to reshape the sectors perception, to provide evidences of real success and replicable models to follow, as well as to promote the take-off for the utilisation of APPR biomass residues.

WASTE2FUELS (H2020) aims to develop next generation biofuel technologies converting agrofood waste (AFW) streams into high quality biobutanol. WASTE2FUELS aims at the development of novel pretreatment methods, enlarging current available biomass for biofuels production. It targets the development of new routes for biobutanol production via ethanol catalytic conversion through the development of genetically modified microorganisms and biofilm reactor systems for enhancing conversion efficiencies of fermentation.

The objective of **CoolHeating** (H2020) is to support the implementation of small modular renewable heating and cooling grids. This will be achieved through knowledge transfer and mutual activities of partners between countries with different experience on renewable district heating and cooling. Core activities, besides techno-economical assessments, include measures to stimulate the set-up district heating systems as well as capacity building about financing and business models.

BIOREG (H2020) will create a platform of stakeholders who are able to influence and develop their regions towards bio-based industries and products. Demonstrator case studies regions have set up renewable wood waste-based systems at different stages of the value chain including different sources, pre-sorting, sorting, collection, recycling and treatment (to materials, biochemicals or biofuels) as well as the different gradings and regional wood waste composition in each country.

BIOVOICES (H2020) aims at engaging relevant stakeholder groups voices (policy makers, researchers, business community and civil society) to address societal, environmental and economic challenges related to bio-based products and applications. The platform developed by BIOVoices builds on the concept of Mobilisation & Mutual Learning Platforms and methods developed previously in European projects with the objective of delivering an Action Plan addressing the challenges of raising awareness of and engaging with the citizens on bio-based products.

BIOWAYS (H2020) intends to meet the need for better communication of bio-based products and applications and the benefits they bring focusing on promoting bio-based industries. BIOWAYS proposes a wide range of integrated, high-level activities and tools with added value for communication programmes. Tools being developed include an innovative online collaboration platform and social network, an accessible library of bio-based products, training materials, social hack days, co-creation workshops, an eConference, BarCamps and thematic Charettes.

The main objectives of **EFFORTE** (H2020) are to develop techno-economically feasible methodology to predict trafficability prior to forest operations to increase forest growth and productivity of tree planting and stand management and to develop and pilot modern Big data solutions that increase productivity and decrease negative environmental impact. New knowledge, improved methods and technical development are combined with better transfer of information from different sources (e.g processes, geo data from LiDAR scanning, weather data etc).

FibreNet (H2020) will train young professionals with multidisciplinary view to develop sustainable bio-based fibre products with tailored properties for different application fields in both academic and non-academic sectors. The project proposes a training and research network which provides and develops knowhow, methods and tools in functionalization, characterization, numerical modelling and production of bio-based fibre products at multiple length scales.

GreenCarbon (H2020) goal is to develop new scientific knowledge, capability, technology, and commercial products for biomass-derived carbon materials. This will be accomplished through research and training programmes for early-stage researchers. The programme covers all aspects from precursors (biomass) to processing (thermochemical conversion, porosity development, chemical functionalisation) and application (e.g., CO_2 capture, heterogeneous catalysis and chemicals from biomass) enabling a unique design of engineered sustainable BC materials.

The aim of the **ICRI-BIOM** (H2020) project is to establish a new centre of excellence in the Lodzkie Region, Poland, by creative and collaborative efforts, i.e. TEAMING with Max Planck Society (MPS), Germany, as the internationally leading institution. The planned International Centre for Research on Innovative Bio-based Materials (ICRI-BioM) will focus on design, synthesis, characterization and practical implementations/applications of advanced materials, exemplified by biomaterials, bio-products, and multifunctional smart polymer systems.

STAR-ProBio (H2020) aims to promote a more efficient and harmonized policy regulation framework, to promote the market-pull of bio-based products. This will be achieved through a fit-for-purpose sustainability scheme, including standards, labels and certifica-tions for bio-based products. STAR-ProBio will integrate scientific, engineering, social sciences and humanities-based approaches to formulate guidelines for a common framework promoting the regulations and standards to support business innovation models in the bio-based sector.

WeBio: Web Platform to manage Biosource Potentials for Renewable energy production is a Climate-KIC project that will develop a matchmaking platform to take advantage, in a systematic and optimized manner, of all available resources over a territory. WeBio hence offers to give information to biomaterials, and to energy producers, local authorities and investors. For that latter, the problem is not so much accessing the resource as reaching critical quantities of biowaste to make its conversion into energy a profitable activity.

Horizon scanning the European Bioeconomy (Biohorizons) is a Climate-KIC project focused on mapping the bioeconomy to identify areas for growth, opportunity and innovation. Demographic and climatic changes are putting the world's resources under increasing pressure. The biorefining has the potential to offer new and sustainable sources . However, the bioeconomy market is in its infancy and it is still unclear how its research & commercial outputs can be best put into practice.

The Climate KIC project **ForValor – Improve the European forest value chain** will develop an innovative tool to take stock of regionally available assortments and qualities of wood in the forest based on latest remote sensing and ground truth data. The project will explore the information needs of key players in the forest chain on present and desired future forest data. Together with key players, availability and gaps of existing data will be surveyed and, data requirements on future timber volumes and qualities will be explored.

WoodPickER Climate KIC project analyses the feasibility of a sustainable forest management model in a pilot area. The model integrates advanced sustainable forest exploitation technologies with short rotation forestry and the best biomass valorization options. Engaging stakeholders and analyzing technical, environmental and economic feasibility of the model, WoodPickER allows policy instruments (RuralDevelopmentPlan) to get better value-for-money, generating positive economic outputs and employment opportunities, while reducing GHG emissions and increasing carbon sink.

MuBiGen (Municipal Bioenergy Generation) Climate-KIC project aims at creating a potential business model for an integrated value chain, in which cities produce their own marketable and storable energy carriers and biomaterials from unused urban grass cuttings. The project will demonstrate the potential positive climate impact and prepare the exploitation of the business idea in two cities. Next a European network, which transfers the business idea to other European municipalities, will be prepared for a successful implementation of the business idea.

Based on optical/radar satellite data, **FOREST (Fully Optimised and Reliable Emissions Tool)** Climate-KIC project provides solutions for sustainable forest management and carbon stocks enhancement. FOREST provides forest owners with forest management services. Through the use of optical and radar data, in situ measurements and software (based on the ORCHIDEE model), the project will provide info on the size and structure of forest areas.

4.3 Biochemical processing

4.3.1 Anaerobic digestion: EU and SET Plan projects

A number of 68 projects have been identified as addressing the research on biomass combustion, of which 30 projects under FP7, 12 projects under the IEE programme and 26 projects under H2020 RTD EU programmes. The **FABBIOGAS** (IEE) project aimed at promoting and valorisation and efficient integration of residues from food and beverage industry for biogas production. FABbiogas established an information base on the use of residues for biogas production and maps of biogas plants and waste streams. FABbiogas results comprise the set of tools and guidelines needed for creating a European reference standard on industrial waste use for bio-energy.

BioEnergy Farm II (IEE) focuses on micro scale biogas plants using manure and feed left-overs of farms in order to open the market for micro-scale digestion. A portal to inform the farmers about micro-digesters was made. An online quick scan allows farmers to make a pre-feasibility study. The project prepared a detailed offline feasibility tool to be used by the trained experts. A guidance document for policy makers enables them to improve the conditions for biogas production. A offline feasibility tool can be used to perform the scan providing data as input for the business plans.

The aim of **BIOGAS3** (IEE) was to promote the sustainable production of renewable energy from biogas from agricultural residues and food and beverage industry waste at small-scale. The project aimed to develop a sustainable model for small-scale AD, including an energy demand management model. The project developed business models for funding opportunities, detailed in a handbook and a program to evaluate the sustainability of new small scale biogas plants.

The **GERONIMO** (IEE) project built a user-centered web-based platform which provides farms with access to relevant information technology, tools and financial support on farm energy efficiency and RES. GERONIMO II-BIOGAS quantified the biogas potential from dairy and pig farms and to capacitate them to draw up business plans and strategies for investment in biogas facilities. The project aimed to transfer best practice of pro-biogas policies, schemes and incentives to EU regions to create regional frameworks that remove the barriers that are preventing the uptake of biogas.

GERONIMO II-BIOGAS (IEE) worked closely with dairy and pig farmers to quantify the biogas potential on their farms and to capacitate them to draw up robust business plans and strategies for investment in biogas facilities. The project aimed to transfer best practice in the area of pro-biogas policies, schemes and incentives from frontrunner regions to other EU regions to create pro-biogas regional frameworks that remove the barriers that are preventing the uptake of biogas.

FARMAGAS (IEE) promoted AD of agricultural wastes in European farms, through know-how dissemination and knowledge transfer to farmers in New Member States. The project used the relevant and country specific information and training materials on biogas production at farm level, based on tools and guidelines developed in the project AGROBIOGAS. Training and dissemination activities were performed in local farms.

GreenGasGrids (IEE) aimed at leveraging market development for biomethane through know-how transfer from forerunner to starter countries, finding solutions to market barriers and bring together business partners. The project focuses on the issues of trade, technical standards, legislation and sustainability. Biomethane strategies were targeted to provide decision-makers in starter countries with technical and legislative advice to introduce cost-efficient support measures.

The **BiogasHeat** (IEE) project addressed the problem of how to efficiently use the heat from biogas plants. A set of different policy, best practice, field tests and project implementation measures were developed. New and existing plants in emerging European biogas markets are targeted with concrete solutions to efficiently use the heat to be proposed and demonstrated.

SUSTAINGAS (IEE) has focussed at promoting sustainable biogas supply by positioning sustainable biogas products from organic farming. A tool to describe the economic interaction between biogas and organic food production has been established including criteria for sustainable organic biogas production for the analysis of sustainability performance of organic biogas plants.

The **GR3** (IEE) project promoted the use of grass and other herbaceous residues as a resource for biogas. A biomass quality web tool for predicting the suitability for digestion of grass residues and a calculation web tool for evaluating the techno-economic feasibility and profitability of using grass residues were developed. The project brought key market actors together and provided them with technical, investment and legislative advices and info on best practices.

BIOPROFARM (IEE) addressed the existing barriers in regional context for biomethanisation. It identified administrative, technical barriers and financial barriers in various countries and proposed the necessary specific legal incentives for biogas development. It conducted an awareness campaign by participation on exhibitions and seminars after the identification of the important regional stakeholders to promote biogas production.

The objective of the **SOLROD** (IEE) project was constructing a CHP biogas plant using: seaweed collected from beaches, organic waste from the local industry and manure from local pigs and cattle farms. This contributed to solve problems with aquatic pollution and the reduction of CO_2 emissions by replacing fossil fuels by 40 ktonnes. Biomass treated in the biogas plant (digested biomass) can be used as biological fertilizer which is a more efficient fertilizer than other non-treated biological fertilizers, and as substitute of chemical fertilizers on farmland in the area.

BiogasIN (IEE) aimed to develop a sustainable biogas market in Central and Eastern Europe. The project was designed to address the main bottlenecks for the development of new biogas plants, including complex permitting procedures and inadequate financing mechanisms. The objective was to create awareness on the feasibility and the benefits of biogas production and use and to increase the confidence in biogas production.

BIOMASTER (IEE) goal was to prove that biomethane for transport can be an operational and viable option in spite of the regulatory and fiscal barriers. BIOMASTER focussed on setting up a waste-to-wheel partnership, set-up of networks to involve local stakeholders, to address the potential sources of biomethane, potential for production and use, available distribution modes, and legal, organisational and financial barriers. A key goal was to focus on grid injection, to bridge the knowledge and operational gaps fragmenting the biomethane chain and to foster dialogue.

BIO-METHANE REGIONS (IEE) aimed to stimulate the market development of AD, with emphasis biomethane production, through independent advice to potential developers, regulators and decision makers. The region developed action plans and strategies for moving forward with the overall objective to establish AD, bio-methane to gas grid and bio-methane as a transport fuel as viable and attractive options to investors, waste and energy companies and governments.

The objective of **UrbanBiogas** (IEE) was to promote the use of the fraction of organic urban waste for biogas production to inject biomethane in the gas grid and to use it in transport. The objective was to prepare five cities for the production of biomethane. Support activities were organised: city Task-Force meetings, training courses, promotional campaigns, study tours and consultation events. The network of partner cities was used to promote the concept beyond the target cities.

The **CONDIMON** (FP7) project aimed to develop a sensor system for monitoring oil quality in biogas engines. The prototype sensor system will contain a novel corrosion sensor measuring permittivity, conductivity, viscosity, temperature and moisture to be integrated in a programmable logic controller (PLC) data acquisition system. An algorithm using all measured parameters provides decision support on the maintenance of the generators.

The **THERCHEM** (FP7) project aims to address the thermochemical pre- and post-treatment process for the AD of brewers' spent grains. This will increase the yield and decrease the size of the AD plant. The project has optimised the conditions (temperature, pressure and duration) for the pre-treatment of brewers' spent grains with sulphuric acid. A post-treatment trickle bed has been designed to remove unwanted hydrogen sulphide gas by converting it into hydrogen sulphate.

PHASEPLIT (FP7) aimed to develop a decentralized wastewater reactor for electricity and heat, for food and drink industry. Phaseplit is based on two-phase AD process, separated acidogenic and the methanogenic stages. This allows optimization of both stages, maximizing the benefits. The project performed tests on lab and pilot scale. This will maximize COD removal from wastewater in the food and drink and for wastewater with high content of organic matter (sugar, fats and proteins).

The project **VALORGAS** (FP7) aimed to overcome the challenges related to collection, handling, pre-treatment and the AD of food waste to recover a gaseous fuel. The project set out to evaluate the efficiency and yield of food waste collection scheme. It addressed the anaerobic microbial interactions to achieve stable operating conditions at high loading rates and efficiencies. This product may be used for heat and power production and as a fuel for vehicles.

The **BioROBUR** (FP7) project plans to develop a fuel processor for the direct reforming of biogas and test on a PEM-grade hydrogen production unit. The project adopted an autothermal reforming route, based on easily-recoverable noble-metal catalysts. The project proposes adoption of a multifunctional catalytic wall-flow trap based on transition metal catalysts, coupled to the ATR reformer and the adoption of a coke growth control based on periodic pulses of air/steam for an on-stream regeneration of the catalysts.

The **OPTI-VFA** (FP7) project aims at developing a prototype of a novel monitoring and control system based on online volatile fatty acid (VFA) measurement in AD plants. The prototype uses infrared light to detect changes in VFA concentrations within the digester, and control is achieved through a user-friendly software interface. Lab testing measuring online VFA concentrations was followed by pilot testing.

The **SMART TANK** (FP7) project was set to develop an autonomous thermophilic digester. The project reviewed the thermophilic ADs, and studied the effects of various conditions on metabolic rates of the bacteria. Sensors and actuators that could be used to monitor and control these conditions were identified. The project built a mobile prototype and then a permanent prototype for testing and process optimisation.

The **BiFFiO** (FP7) project proposes to mix the waste from fish farms and manure from agriculture in a reactor for the production of biogas. The BiFFiO project aims to develop a novel technology for handling mixed waste for energy production, and further use of the digestate, using a three-stage system of pre-treatment, biogas reactor and fertilizer recuperation.

The **ADAW** (FP7) project addresses AD of slaughterhouse waste for biogas production. The project aims at improving biogas yields by using a saponification pre-treatment by unifying saponification and sterilisation and/or pasteurisation processes. It also aims improving biogas yields by selecting specific bacteria and by advance control system for real time monitoring.

The **BIOMAN** (FP7) project addresses biogas production from manure and straw by improving physical and enzymatic pre-treatment. After chemical characterisation of several substrates with high lignocellulose content, measurements were performed to assess potential biomethane production. Substrates were analysed before and after tests on different handling equipment, different enzymatic treatments and ultrasound.

The **MICRODE** (FP7) project will address the issue of enzymatic degradation of biomass by using an inter-disciplinary approach to study and compare natural and engineered digestive ecosystems. The project will provide insight into diverse microbial lineages and uncover core enzyme for biomass degradation. Relevant genes identified from reconstructed genomes and/or transcriptome data for isolates will be cloned and characterized in detail.

The **ATBEST** (FP7) training network will develop innovative research and training for the biogas industry in Europe. The aim is to establish long-term collaborations and develop structured research and training relevant to industry and academia along the biogas supply chain.

The **AD-WISE** (FP7) project developed a novel approach for monitoring AD plant performance, with a real-time system that measures single volatile fatty acid (VFA) concentration to determine AD efficiency. An in-line real-time sensor is used by specifically designed software to advise the biogas plant operator on how to optimise the plant operation. A prototype was installed at an industrial-scale AD plant for extensive testing.

INEMAD (FP7) aims to develop strategies to better integrate nutrient and energy flows in agriculture and reconnect livestock and crop production farming systems. INEMAD has assessed nutrient management at the farm level, current policy and potential strategies for processing of farm wastes. INEMAD will analyse improvements options for biogas plants, valorisation options for the digestate, improve the management by the use of optimisation models.

The **AD-WINE** (FP7) project aimed to develop an anaerobic treatment system of wineries' effluents. The project focused on the evaluation of the viability and application of high performance AD. A prototype of a digester will be developed and followed by a theoretical and calculation model for the AD process. The design and operation parameters of the treatment technology will be optimized.

The project **BIOWET** (FP7) was launched to investigate several ways to use biological waste for electricity production. These consist in AD of wastewater and solid waste, bio-hydrogen production from industrial wastewater and electricity production using fuel cells. The project is fostering sharing of ideas and information among partners and to young and experienced researchers in this and related fields.

The focus of the **3CBIOTECH** (FP7) project was gaining better understanding of the microbiology of low-temperature AD and characterise microbial communities underpinning novel and innovative, low-temperature, anaerobic waste conversion, including municipal wastewater treatment and biorefinery applications. The work will include organic acid-oxidizing, hydrogen-producing syntrophic microbes and hydrogen-consuming methanogens.

The goal of the **F2W2F** (FP7) project was the demonstration of a closed cycle organic waste treatment system to increase the use of organic waste as input for a closed-loop process for crop production. The proposed integrated system covers organic waste pre-treatment, anaerobic digester for digesting the waste, creating biogas for CHP, liquid effluent as fertiliser and digestate separation.

The **PLASMANURE** (FP7) project aimed to reduce the ammonia emissions from pig waste by developing a cost-effective optimized plasma-catalyst reactor for manure waste, with direct economic benefits by reducing costs of ammonia removal (pH control, stripping-scrubbing sequences, etc.). The technology could enhance existing treatments by facilitating the oxidation of ammonia from pig manure into nitrogen gas and water vapour.

The **ROUTES** (FP7) project investigated ways to process and to sanitise sludge for further use in agriculture. One process involved a thermal pre-treatment at 135 °C, followed by AD. One technique for minimising sludge production was the use of a SBBGR biofilter, which was able to produce granular biomass and microbial electrolytic cells. An innovative wet oxidation process proved to be a suitable alternative for disposal of the sludge to incineration.

ORION (FP7aimed to develop a small automatic user-friendly digestion unit for on-site treatment of between 100 and 5000 tonnes per year organic waste. This will provide a practical solution to the agro-food industry and the waste-processing industry to dispose of relatively small amounts of organic waste and create energy. The different modules (hydrolysis, digestion, combustion, control systems and active surfaces for bacteria) of the AD system were designed and tested.

ANAMIX (FP7) was dedicated to study and improve biological generation of chemicals and energy carriers from organic residues generated by agro-industrial activities. The goal was to identify and verify the biochemical driving forces for the establishment of specific production processes in mixed microbial environments. Valuable and realistic products are hydrogen, methane rich biogas, solvents like ethanol and butanol, or the generation of electricity in so called microbial fuel cells.

LEGUVAL (FP7) project targeted the valorisation of co-products and by-products of processed legumes production by extraction of the protein fraction and use of the leftover biomass as additives and as a source of biogas by AD. Methods to process materials have been investigated and various by-products have been identified.

The **NUTREC** (FP7) project focuses on the recovery of ammonia (N) and phosphorus (P) from wastewater, in particular from biogas production (rich in N and P) and leachates (rich in N) from landfills. NUTREC wishes to improve and optimize a new, innovative technological process for recovering ammonia, and extending such process for the recovery of phosphorus from diverse wastewaters, and transforming the nutrient-rich by-streams into useful fertilisers.

PLASCARB (FP7) will integrate AD with innovative, low temperature microwave plasma processing and carbon morphology and purification. The project will transform the biogas using innovative low energy microwave plasma to split biogas methane into high value graphitic carbon and renewable hydrogen. The project carried out continuous operation at pilot scale where mixed food waste was used to generate biogas, which will then be transformed into a range of high value carbon materials.

The **LTANITRO** (FP7) project provides a new approach for the treatment of wastewater. The innovative microbiological process involves the anammox bacteria that 'shortcut' the conventional nitrogen removal of treatment plants, producing revenue by biogas production.

BIOWASTE4SP (FP7) aimed to develop biotechnological processes for converting biodegradable fractions of African and Mediterranean agri and industrial waste as well as municipal and animal solid waste into food, feed, value-added products for nutraceuticals and healthcare, biogas and fertilizer. Integrated processes combine sugar conversion from various materials into proteins with biogas and fertilizer production done in co-digestion of municipal solid waste and manure.

WASTE2GO (FP7) project aimed to develop and verify technologies that can transform MSW into a source of sustainable, high-value chemicals. Novel enzyme-based systems have been developed to digest, or breakdown, MSW. These enzymes are now produced in large volumes to facilitate small-scale digestion trials. The project introduced two novel engineering systems to extract valuable chemicals at every stage of the digestion process.

BIOFERLUDAN (H2020) targets the development of an on-site recovery process, cost-effective and reliable treatment for the digestate. The project aims to implement a new process to obtain liquid fertilizers with high organic matter content, in form of humic substances, recovering them from the digestate. It will constitute a business and improvement opportunity for biogas plants.

The aim of the **Waste2bioHy** (H2020) project is to investigate fundamentals of microbial communities involved in fermentative/electrogenic bioprocesses. The project aimed the development of a cascade two-step BioH2 production, combining dark fermentation and microbial electrolysis cell. Several waste streams were evaluated for coupling dark fermentation and microbial electrolysis cell processes to maximize H_2 recovery. Several inocula were evaluated and selected and characterized for dark fermentation and microbial electrolysis cell processes.

The **ADD-ON** (H2020) project will scale up current pilot equipment to demonstrate at industrial scale of a nitrogen-control technology that capable to remove over 60% of nitrogen from several organic waste materials. This enables broader utilisation of high-nitrogen organic waste such as chicken manure in biogas production and chicken manure can replace maize silage as biogas feedstock.

The objective of **Bin2Grid** (H2020) concept was to promote segregated collection of food waste as energy source, conversion to biogas, and its upgrading to biomethane. Strategies will be defined for establishing efficient network of food and beverage waste collection methods and practices. Particular attention will be given to advanced biogas to biomethane upgrading techniques for purification and technical requirements for its usage through local filling stations.

The project **Bio-HyPP** (H2020) aims to develop a full scale technology demonstrator of a hybrid power plant using biogas, a micro gas turbine (MGT) and a solid oxide fuel cell (SOFC). The demo plant aims to prove the concept, followed by detailed characterization and optimization of system integration. The MGT and SOFC have to be optimized by a multidisciplinary design approach using numerical and experimental data. An integrated control system has to be developed to achieve a reliable operation of the coupled subsystems.

BiogasAction (H2020) aim to serve as vehicle for the development of the European biogas sector and thereby contribute to the EU 2020 targets by focusing on removing non-technical barriers to widespread production of biogas/biomethane from manure and other waste. Central driver is the cooperation between different policy levels at EU, national and regional level. The project will boost local biogas development in conjunction with replication efforts & promotion at broad EU scale.

BIOGASTIGER (H2020) is a modular compact biogas plant in a transportable container construction. All components are standardized and industrially pre-manufactured in series, tested for quality before delivery and on site installed and commissioned with short assembly times. This concept leads to the best cost to efficiency ratio, to the highest flexibility and stable energy supply on request.

BIONICO (H2020) will develop, build and demonstrate a novel reactor (100 kg/day) concept, at a real biogas plant, integrating H_2 production and separation in a single vessel. The methane will be converted to H_2 at a lower temperature. Direct conversion of biogas to H_2 is achieved in a single step. BIONICO will demonstrate the membrane reactor at a larger scale, with more than 100 membranes implemented in a single fluidized bed membrane reactor. BIONICO process will demonstrate to achieve an overall efficiency up to 72% due to process intensification.

BioROBURplus (H2020) builds upon the previous FCH JU BioROBUR project (direct biogas oxidative steam reformer) to develop a pre-commercial fuel processor delivering 50 Nm^3/h H_2 from biogas from landfill gas, AD of organic waste, or wastewater-treatment sludge. The energy efficiency of biogas conversion into H_2 will exceed 80%. The process will entail increased heat recovery, a tailored pressure-temperature-swing adsorption (PTSA) and a recuperative burner capable of exploiting the low enthalpy gas to provide heat.

BIOSURF (H2020) focusses on the development of a biomethane market by promoting collaboration of national registries. BIOSURF aims to increase the production and use of biomethane, by removing non-technical barriers. BIOSURF will perform a value chain analysis for biofuel for transport, electricity, heating & cooling. It will analyse, compare and promote biomethane registering, labelling, certification and trade practices, to promote cooperation cross border markets.

The objective of **DEMETER** (H2020) is to increase the yield of this industrial fermentation process, improve the product recovery process, and reduce overall product cost while increasing the productivity. DEMETER will demonstrate the efficacy of a C1-LC4 enzyme previously developed, that will be tested on lab and small pilot-scale, obtaining insights for scale-up. The effect of enzymes will be quantified, using 5 commonly used biomass substrates. The improved fermentation and downstream process will be scaled up and demonstrated in a 15 000 L pilot plant.

The **DEMOSOFC** (H2020) objectives are the demonstration and analysis of an innovative solution of distributed CHP system based on SOFC, for low capacity distributed CHP. Another objective is the demonstration of a distributed CHP system fed by a biogenous CO2 neutral fuel: biogas from AD in a real industrial installation. DEMOSOFC will prove the high performances of such systems: electrical efficiency, thermal recovery, low emissions, plant integration, economic interest for best use of renewable fuels in a future of decreasing incentives.

The **ENGICOIN** (H2020) project aims at the development of three new microbial factories (MFs), integrated in an organic waste AD platform, based on engineered strains exploiting CO_2 sources and solar radiation or H2 for the production of value-added chemicals (TRL 3 to TRL 5). This includes: produce lactic acid from biogas combustion flue gases or CO_2 from biogas purification; produce PHA bioplastics from biogas combustion flue gases and carbon from the AD; produce acetone from CO_2 from biogas purification.

The overall aim of the **H2AD-aFDPI** (H2020) project is the development and field trials for a novel micro-scale technology for the disposal of organic effluent based on a hybrid of Microbial Fuel Cells (MFC) and AD (TRL6/7). H2AD-aFDPI aims to prove commercial viability for efficient removal of organic content from waste streams; slurry; and post-AD liquors. The project seeks to develop sensing for automated/remote control of system operation and optimised biogas yields.

HOMEBIOGAS (H2020) develops and markets advanced biogas systems that reduce waste management fees, energy cost and environmental footprint by converting organic waste to biogas. The project aims to offer an affordable (€10,000), high performance biogas solution to specific needs that will convert organic waste (100 kg per day) into clean energy (120 kWh per day), generating important savings (over €5,000 per year). HOMEBIOGAS TG6 has been demonstrated at TRL6 through the development and trial of two large (200-250 kg per day) pilots.

The main **ISAAC** (H2020) project objective consists on the construction of a communicative model oriented to spread balanced information, based on environmental and economic benefits of biogas/biomethane. Actions will focus on reducing the fragmentation between stakeholders to reach the minimal facility dimension, increased biogas/biomethane penetration . The project will propose a participatory process model to reduce social conflict and to include all actors in decision making process and a normative proposal on the participatory process.

ISABEL (H2020) aims to remove the obstacles and to promote community biogas by bringing out its societal relevance. ISABEL employs modern marketing research to understand the needs and cultural diversities of the communities, fuses Social Innovation to reposition Biogas from an economic bio-fuel 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.

The **Lt-AD** (H2020) project proposes a novel low-temperature (4 - 20°C) AD solution for wastewater at ambient temperatures for the Food and Drinks sectors. The Lt-AD technology has a compact design and produces negligible sludge volumes and effluent at urban wastewater standard (< 125 mg/L COD) without post-aeration and requires no heat input or biogas recirculation. This Phase 2 project will allow the installation and commissioning of a demonstrator plant.

In the **NTPLEASURE** (H2020) project, an integrated separation-nonthermal plasma (NTP)-catalyst system will be developed to enable the biogas utilization. The system will be based on selective capture of CO_2 from biogas with ultra-thin SAPO-34 zeolite membranes (~1 μm) and subsequent NTP-assisted catalytic CO_2 methanation on Ni- and/or Co-based catalysts supported on 5A zeolite membrane (~3 μm). The design combines CO_2 capture and methanation at ambient temperature.

The **OptiMADMix** (H2020) project aims to deliver a methodology to improve mesophilic AD' design and control, reducing energy consumption and maximising biogas production. It will provide a numerical framework to optimize the digester performance. The complex relationships between hydrodynamic and microbiological processes will be simulated, and coupled CFD/AD modelling will be used to monitor and control the hydraulic and biochemical performance, to improve digester control, eliminating environmental and financial costs whilst maximising biogas output.

The project **POWERSTEP** (H2020) aimed to demonstrate innovative concepts at full scale to design energy positive wastewater treatment plants. The project planned 6 full-scale case studies: enhanced carbon extraction (pre-filtration), innovative nitrogen removal processes, power-to-gas (biogas upgrade), heat-to-power concepts (CHP unit, steam rankine cycle, heat storage concepts), and innovative process water treatment (nitritation, membrane ammonia stripping).

Primary objective of the **Prometheus-5** (H2020) project is the development of a decentralized (on or off grid) power generation unit to convert the fuel (LPG/NG/Biogas) into electrical and thermal power through a PEM fuel cell, with intermediate production of H_2. The nominal capacity of the power system is 5 kWe and 7 kW of thermal energy and electrical efficiency above 35%.

The objective of **Record Biomap** (H2020) is to establish innovative process and technology solutions along the biomethane supply chain (pre-treatment, digestion, gas conditioning/digestate utilisation) and to support their development up to market uptake. The project enabled knowledge transfer from science to market and policy decision-makers through building up a biomethane platform for networking. The project contributes to identify financing sources bringing together stakeholders for the development of cost and efficient biomethane production at small-medium scale.

The **SHEPHERD** (H2020) project will improve an existing prototype of on-line microbial respirometer for monitoring the activity of the microbial population in activated sludge for wastewater applications (TRL 6 to TRL 8). The integration with existing hardware sensors and SCADA systems, allows the automatic control the plant within design operating parameters and reacting in real-time to variable loading or toxic events. The project aims to take the technology forward, automate the process to a higher degree and demonstrate the solution in a large-scale pilot.

VegWaMus CirCrop (H2020) aims to develop commercial mushroom and vegetable production in an integrated food to waste to food system. The project objective is closing loop between biogas production from food wastes and reuse of output. Mushroom and plant crop cultivation is performed through energy- and resource-intensive process, generates waste and the high CO_2 footprint. The unit will investigate and demonstrate full utilization CO_2, heat and digestate from AD.

VicInAqua (H2020) aims to develop a sustainable combined sanitation and recirculating aquaculture system for wastewater treatment and reuse in agriculture in the Victoria Lake basin area. The concept is to develop and test a novel self-cleaning water filters consisting of a highly efficient particle filter as well as a membrane bioreactor as principal treatment unit within a combined treatment system where the nutrient rich effluent water will be used for irrigation and the surplus sludge will be co-digested with agricultural waste and wastewater to produce biogas.

The **PHARM AD** (H2020) project will address use of AD for the removal of pharmaceutical residues not only in conventional treatment of sludges, but also on the novel application of AD to the direct treatment of waste waters rich in these pollutants (e.g. hospital or industry). It will also try to combine pharmaceutical residues removal by AD with biological nutrient removal (nitrogen) by micro-algae cultivation, thus addressing one of the drawbacks of AD: the lack of nitrogen removal.

The **VERBIO** (SET-Plan flagship) project, supported by the NER300 and recognised by the SET-PLAN as a flagship initiative, aims to demonstrate an innovative AD technology to produce biomethane from straw. The plant in Schwedt/Oderand has a capacity of 16.5 MW, using 40000 tonnes/yr of straw. Biomethane can be purified to natural gas quality and fed into the gas grid. The raw material (straw) is fermented to produce raw biogas, containing impurities that are removed in the next steps The resulting biomethane with a purity of 99% is then fed into the natural gas grid.

The **GoBioM** (Biomethane supply chain technological optimization) project is a funded by the Regional Operational Program-European Regional Development Fund FESR Emilia-Romagna Italy and a SET-Plan flagship project on biogas upgrading optimization to biomethane. GoBioM objectives include: optimize the up-grading technology; build optimal supply chain; analytical protocols for biomass characterization and process control; optimize pre-treatment; exploiting CO_2 for algae cultivation; analyze the environmental, social and technical-economic sustainability.

BioMethER (Biomethane Emilia-Romagna Regional system) is a SET-Plan flagship project cofinanced by the EU LIFE program and the Emilia-Romagna Region. BioMethER aims at boosting the biomethane value chain by building two demo plants for biomethane production for grid injection. This refers to the realization, optimization and operation of a demo plant for landfill biogas upgrade and direct injection in the gas grid at the HERAmbiente site in Ravenna. A demo plant for biomethane production from AD of wastewater treatment sludge will be designed, optimized and made operational at the IREN Rinnovabili site of Roncocesi.

ChainCraft SET-Plan flagship has developed a platform technology, based on mixed culture fermentation, to produce biobased chemicals. The use of food waste for medium chain fatty acids production is investigated at a demo plant facility, processing 40 t food waste/day, by ChainCraft in Amsterdam, the Netherlands (SET-Plan flagship project). Volatile fatty acids from microbial degradation are converted to medium chain fatty acids: caproate, which is a potential valuable platform chemical that can be further converted into chemicals and biodiesel.

The demonstration plant **Cosyma** (Container-based System for Methanation) of PSI (SET-Plan flagship project), Switzerland, has the goal to investigate the technical and economic viability of different power-to-gas technologies since 2016. Methane is produced from biological waste and sewage sludge in AD plants and fed into the natural gas grid. PSI technology allows increasing the methane yield by adding H_2 to the raw biogas and letting the CO_2 react with the H_2 in a fluidised bed reactor, with a nickel catalyst.

ARIES Climate KIC project aims to bridge the gap between small biogas production units and larger gas distribution networks. The project addresses biogas upgrading of biomethane, and the definition of a sustainable integration of biomethane production units in farms (often remote and without nearby access to natural gas network). The solution will integrate financial and environmental dimensions of sustainability. Local reuse of biogas will then be privileged when possible, and cost-benefit analysis will be conducted for different sizes of production units.

The **Biogas2Market** Climate-KIC project addresses business opportunities for sustainable biogas production. Conventional biogas production chains, including the cultivation of raw materials, leakage conversion and storage systems; lead to the emission of GHG , such as methane and nitrogen oxide.Significant financial governmental support is still required to make the traditional biogas production market competitive.

Biogas, Energising the Countryside (Biogas ETC) is a Climate-KIC project and intends to make the use of agricultural waste gases a useful resource for biogas production and economically viable at remote locations for small-scale producers. The project develops a low-cost small-scale gas conversion device to be installed on farms that will accelerate Europe’s transition towards a decentralised supply of sustainable energy.

Fugitive Methane Emissions from hard-to tackle sites and sources (FuME) Climate-KIC project seeks to improve the detection and quantification of fugitive emissions by developing a Methane Measurement Service. FuME will develop three products. The Methane Impact Assessment and Sensor Placement Tool will allow the forecast the quantity and distribution of emissions. A Methane Measurement Service will provide a calibrated sensor network for the continuous and accurate monitoring of fugitive methane emissions. A third product Methane Boundary Fence Leak Detection Instrument, based on a diode laser system will increase the accuracy of detection levels.

The **VERBIO** (SET-Plan flagship) project, recognised by the SET-PLAN as a flagship initiative, received €22.3m funding from the NER300 programme. It aims to demonstrate an innovative AD technology to produce biomethane from straw. The plant will have a capacity of 25.6 Mm^3 of biogas containing 12.8 Mm^3 of methane from the use of 70000 t/year of straw. The process comprises biomass pre-treatment by steam and enzymes, production of biogas by anaerobic fermentation, and biogas post-treatment that will be fed into the grid. VERBIO is to be built as an extension to an existing ethanol-biogas plant in Schwedt, Germany, to produce biogas.

Kalmari farm in Laukaa, Finland, is an example of small scale farm-based biogas production in Finland from cow manure, by-products and energy crops (grass silage). The first biogas reactor with CHP started in 1998. Biogas has been upgraded to vehicle fuel since 2002. Raw biogas is used in a converted engine with 25 kW electric capacity. Biogas is upgraded to biomethane and pressurized to 270 bars using a high pressure water scrubbing unit. The farm project has also given a trigger for a company, Metener, that provides complete biogas systems and carries out development of biogas upgrading for automotive use from small low cost to larger scale plants.

4.4 Thermochemical processing

4.4.1 Biomass combustion: EU and SET Plan projects

A number of 41 projects have been identified as addressing the research on biomass combustion, of which 21 projects under FP7, and 20 projects under H2020 RTD EU programmes. **BIOCAT** (FP7) project investigated ways to integrate a catalyst into wood stoves to improve the burning process and reduce emissions. It tested various catalytic materials and involved simulating the behaviour of a small-scale stove in the laboratory. The team developed methods to assess and optimise the performance of an integrated catalytic system. Prototypes were created and tested and the BIOCAT has produced a number of new heating appliances with little or no carbon emissions.

The **EU-UltraLowDust** (FP7) project aimed to demonstrate ultra-low emission, small-scale novel biomass combustion technologies, for the whole range of residential biomass heating applications. This included a new ultra-low emission pellet and woodchips combustion boiler, a new stove technology based on optimised air staging and an automated control system and a new ESP system for logwood boilers, stoves as well as boilers for non-wood biomass. The project aims at the development of recommendations for future emission limits.

The **ASHMELT** (FP7) project aimed to promote the use of wood pellets by developing a guide on fuel quality and to advance the testing methods and help overcome operational problems due to ash-related issues. Different applied methods to determine chemical and physical fuel properties were reviewed and used to determine the ash content under specified conditions. The ASHMELT set up quality specifications to describe different grades of wood pellets and are the basis for the development of a European standard.

The main objective of the **ENERCORN** (FP7) project was to design, develop, construct and demonstrate a grid connected 16 MW high energy efficient power plant in Spain 100% fuelled with corn stover. The project objective was to demonstrate the plant high operation availability, its overall economic and technical feasibility, and to encourage the development of further similar biomass power plants.

The **BIOLIQUIDS-CHP** (FP7) project focused on new CHP systems using a variety of bioliquids including pyrolysis oil. The project developed an internal combustion engine using pyrolysis with oil-resistant engine parts and a second one with a generator, exhaust gas cleaning system, heat unit and control system. The project also developed an external combustion engine compatible with any heat source with a temperature range of 50 to 1000 °C. Modified design of the micro gas turbine combustion chamber enabled a reduction of emissions using biodiesel and vegetable oil.

The **BIOCHIPFEEDING** (FP7) project developed a new woodchips feeding system for small-scale heating plants that will overcome all current drawbacks. The project proposed a new system based on a gripper, equipped with sensors to screen the fuel quality in terms of particle size and moisture content. Intelligent software that communicates with the feeding system can map locations of low- or high-grade woodchip.

The **GREENEST** (FP7) project focused on a new approach based on a high pressure air-steam gas turbine cycle, with the ability to burn H2-rich fuels. The goal is to investigate the fundamentals of ultra-wet combustion to develop the technology for a prototype combustor which is capable of burning natural gas, hydrogen and fuels from coal or biowaste gasification at low NOx emissions. Research includes the combustion process, the aerodynamic design, acoustics and control.

The **SYNGAS** (FP7) project aimed at numerically characterizing the burning behaviour of premixed syngas and biogas combustion and developing large eddy simulation (LES) techniques to facilitate the study and design of combustion systems. The project will carry out numerical investigations of the development of syngas premixed flames, influence of high-pressure and diffusion effects and develop a turbulent reacting flow model.

The **HRC POWER** (FP7) proposes a concept relying on a hybrid system that combines a number of RES technologies. This **hybrid** renewable converter (HRC) is heated either by micro-combustion that generates high temperature heat from biogas or hydrogen, or by concentrated solar radiation, which shall be converted into electricity. The work focus on simulation, design and developing and testing novel materials (silicon–carbide) for advanced building blocks for high temperatures.

The **BioMaxEff** (FP7) project aimed at the demonstration of ultra-low emission and highest efficiency performance small scale biomass boilers under real life operation. The project addressed with a natural draught log wood boiler and a product series of a 10 to 26 kW (and 60 kW), and a 6 to 12 kW pellets boiler. The pellets boilers were demonstrated solely or in combination with modular components, such as a flue gas heat exchanger and an electrostatic precipitator.

BIOCHARISMA (FP7) addressed the application of biochar to soil as a novel approach to establish a significant long-term sink for carbon dioxide. The production of biochar and its application to soil is expected to deliver immediate benefits through improved soil fertility and increased crop production. The capacity of Mediterranean soils to store and sequester C due to addition of biochar produced from vegetation residues and urban wastes.

The **FLEXI BURN CFB** (FP7) project aimed to develop and demonstrate a power plant concept that allows flexible high-efficiency air-firing of fossil fuels with biomass and oxygen-firing with carbon capture which provides the potential for an almost 100% CO_2 reduction. The project conducted demo tests at a first-of-its-kind 30 MWth air-oxygen-flexible CFB pilot and validation tests at the world's first and largest supercritical once through CFB (460 MWe Lagisza in Poland) for the upgrade to commercial scale FLEXI BURN power plant.

DEBCO (FP7) aimed to demonstrate and assess, on a long term basis, the advanced and innovative co-firing techniques for higher shares of biomass up to 50% more through research, large-scale demonstrations and long-term monitoring of the key co-firing concepts. The project will allow a long-term monitoring and assessment of different fuel supply chain scenarios, fuel qualities, and advanced co-firing techniques.

MACPLUS (FP7) project aimed to increase the performances of combustion power plants by increasing steam temperature and pressure in new ultra supercritical power plants (350-370 bar, 700/720°C minimum), and hence increase the severity of fireside operating conditions. Full-scale prototypes of the critical components, able to withstand co-combustion and high temperatures, had to be realised and installed into an industrial plant for testing.

PITAGORAS (FP7) investigated a cost-effective and high efficiency large scale energy generation system using medium (150-400 ºC) and low (30-150 ºC) temperature waste heat. An Organic Rankine Cycle for heat and power system will be developed together with waste heat recovery and energy storage. The concept will be demonstrated in two cities: Brescia (Italy) and Graz (Austria). Solar thermal energy (10,000 m^2) will be added as support energy system in the city of Graz.

The objective of the **SUNSTORE 4** (FP7) project was to demonstrate a concept of a large scale 100% RES system for district heating (28,000 MWh) in Marstal, DK. This is based on 55 % solar energy and 45 % bioenergy, including a CO_2 heat pump and biomass ORC unit. The plant comprises: 15 000 m^2 solar system, CHP system with a 4 MW thermal oil boiler and a 750 kWel ORC; 75 000 m^3 pit heat storage, 1.5 MWth CO_2 heat pump, supplementing the existing demo plant (SUNSTORE 2) with 18 300 m^2 solar thermal and 10 340 m^3 pit storage.

The **LOVE** (FP7) project sought to develop cost-effective technologies for converting low-temperature (less than 120 °C) waste heat sources into electricity. The project defined a methodology for optimal integration of thermodynamic cycles. Two 100 kWel ORC prototypes were integrated into 2 pilot cement plants, including newly designed components (radial inflow turbine, finned tube of polymeric gas–liquid heat exchangers). A detailed techno-economic assessment for low-temperature waste heat recovery was done.

The **FOUNDENERGY** (FP7) project was set up to reuse the waste heat from foundry industry by developing a cost effective Waste Heat Recovery system for Power Generation, based on ORC process, to produce electrical energy. The project aimed to develop a cost-effective and low-maintenance Waste Energy Recovery Boiler (WERB) suited to the extreme environment, a Waste Heat Recovery System (WHRS) with an advanced guidance and control system and then the integration and optimization of WHRS prototype and the ORC.

The project **ICARUS** (FP7) developed a 5 kW ORC prototype that provides cost-effective heat recovery and generates electricity from low-temperature waste heat of 60-120 °C. It developed thermodynamic models to evaluate the most suitable working fluid in terms of efficiency and operating pressure. The main result of the project is a design for a 20 kW ORC absorption system.

The **UP-THERM** (FP7) project developed an innovative heat engine that is a viable alternative to conventional heat engines. The system is based on an external combustion engine and a novel heat converter, based on the use of working fluids changing phase. Fundamental research into thermodynamics, heat transfer and fluid mechanics has been done to select the suitable fluid. UP-THERM planned to produce and test a 1-3 kWe engine CHP prototype to prove its viability.

DemoCLOCK (FP7) aimed to demonstrate the technical, economic and environmental feasibility for implementing packed bed based high temperature high pressure Chemical Looping Combustion in large-scale power plants. The tests were done on a medium sized (500 kW) fixed bed reactor integrated in an Integrated Gasification Combined Cycle (IGCC) power plant at Elcogas to convert raw syngas to energy. The packed bed reactor technology opens possibilities of using multiple fuels.

The project **Bio-HyPP** (H2020) aimed to develop a full scale technology demonstrator of a hybrid power plant using biogas as main fuel in lab environment, combining a micro gas turbine (MGT) and a solid oxide fuel cell (SOFC). The focus of the technology demonstration plant is to prove the functional capability of the plant concept, followed by detailed characterization and optimization of the integration of both subsystems.

The project **Biofficiency** (H2020) will investigate how to handle ash-related problems in order to increase steam temperature up to 600°C in biomass CHP plants, in pulverised and fluidised bed systems. The goal is to deepen the understanding of fly ash formation, to improve current pre-treatment technologies, as well as to contribute to the field of biomass ash utilisation. The project addresses current bottlenecks in biomass combustion, namely enhanced deposit formation, corrosion and ash utilisation by a variety of new, promising technologies.

The **CYCLOMB** (H2020) project aims to upgrade and scale-up an integrated solution for biomass combustion, achieving 96-99% PM emission reduction, combining flue gas recycling and cyclone variable geometry. Recirculation of flue gases provides the biomass boiler with high combustion efficiency (95%) and reduces boiler emissions from 150 mg/m^3 of typical boilers to 80 mg/m^3. By using a variable-geometry, ≥96-99% PM reduction is achieved, with emission levels below 20 mg/m^3. The PM cyclone-technology solution will be optimized for medium-scale (200 kW-5 MW).

The **HPC4E** (H2020) project aims to apply the new High Performance Computing (HPC) techniques to energy applications, going beyond the state-of-the-art in the HPC simulations for different energy sources including efficient combustion systems for biomass fuels. The next generation of HPC systems will be able to run combustion simulations required to design efficient furnaces, engines, clean burning vehicles and power plants.

HYBURN (H2020) will be developing advanced laser measurement techniques for use in high-pressure combustion test facilities and using them to acquire the data necessary to develop robust predictive analysis tools for hydrogen-enriched natural gas combustor technology. This data will be analysed in close collaboration with the simulation and modelling teams and used to rigorously test and validate combustion models and predictive analysis tools currently under development.

The **MILESTONE** (H2020) project aims to establish a new multi-scale framework to analyse and model turbulent combustion phenomena based on a new way to describe turbulence using so-called dissipation elements, which are space-filling regions in a scalar field allowing to capture its small-scale morphology and non-universality. The project will create new datasets using numerical simulations and provide new analysis methods to develop and validate combustion models.

The **RECOMBIO** (H2020) project deals with development and demonstration of innovative approaches to efficient co-utilisation of low quality biomasses and Solid Recovered Fuels produced from municipal solid waste. Different technologies, such as circulating and bubbling fluidised beds (CFB, BFB), are incorporated to demonstrate the highly efficient utilisation chain for the intelligent co-utilisation of low quality biomass and SRF. RECOMBIO proposed to perform a number of demonstrations of relevant SRF production and utilisation technologies.

The overall objective of **Residue2Heat** (H2020) is to enable the utilization of ash-rich biomass and residues in residential heating applications (20-200 kWth). In this concept, various agricultural and forestry residue streams are converted into a liquid energy carrier at a scale of 15-30 MWth using the fast pyrolysis process. The fast pyrolysis bio-oil is distributed to a large number of residential end-users. Residue2Heat will perform the modification of existing condensing boilers and low emission blue-flame type burner to enable the use of the fast pyrolysis bio-oil.

The main objective of **START** (H2020) is to carry out investigations on a prototypical reverse flow, ultra-compact, combustor engine designed by GE-Avio. This will validate the developed technologies and designs by means of full combustion tests and high fidelity numerical simulations. (CFD) will help the design of innovative combustors for addressing the target of SFC reduction faced with the increase of engine cycle efficiency. The validation of innovative additive manufacturing components at TRL5 will positively contribute to reduce costs and weights.

The **TUCLA** (H2020) project aims to develop non-intrusive laser-diagnostic techniques with high spatial and temporal resolution for the measurement of key parameters such as species concentrations and temperatures. The project will use the diagnostic techniques to provide experimental data and enhance the understanding of combustion phenomena. Studies will be carried out on three flame structures: in laminar and turbulent flames; in biomass gasification; and combustion improvement by electric activation.

VADEMECOM (H2020) plans to apply experimental, theoretical, and numerical simulation approaches for the development of combustion technologies. New-generation simulation tools will be developed to increase the fidelity of numerical simulations. Experimental data will be collected to disclose the nature of the interactions between fluid dynamics, chemistry and pollutant formation processes. Experiment and numerical simulations will be tied together by Validation and Uncertainty Quantification techniques, to allow the application of the developed approaches.

The **MefCO2** (SET-Plan flagship) project addresses methanol synthesis high CO_2 concentration-streams as an input and H_2 from water hydrolysis using surplus energy. The demo technology might use biomass combustion and gasification system streams. The process will contribute to the mitigation of exhaust carbon dioxide, stabilisation of electric grid by the consumption of the electric energy at its peaks and the production of methanol as a versatile chemical for further conversion.

Avedøre Power Plant, Unit 2 is a SET-Plan flagship project that aims to build a CHP plant, having two units generating electricity and district heating in Copenhagen. Unit 2 is a multi-fuel plant using biomass. By generating both electricity and heat, the plant utilises up to 94% of the fuel's energy. In addition to this, Unit 2 is one of the most efficient power plants in the world.

The objective of the **DeReco** (H2020) project is to develop and commercialise a small scale (1 to 50 kW) Waste Heat Recovery System (WHR). The WHR-system is based on the Clausius Rankine Cycle (CRC) or alternatively on the Organic Rankine Cycle (ORC). WHR-systems can be adapted to different kinds of heat sources, and in the power generation through biomass combustion as well as in the geothermal and solar thermal energy.

The **NanoORC** (H2020) project aims at developing a general model for the estimation of the thermophysical and transport properties of nanofluids, to evaluate their potential for Organic

Rankine Cycles (ORC). The addition of nanoparticles to fluids (nanofluids) can enhance their thermal properties, making them an optimal solution for their use in ORC. The novelty of the project lies on the use of group contribution methods to develop a generalized model that will be integrated as a property library into simulation software.

The **TASIO** (H2020) project aimed to develop solutions to recover the waste heat using waste heat recovery systems based on ORC. A WHRS will be developed and tested to recover and transform the thermal energy of the flue gases into electricity. It is planned to design and develop a direct heat exchanger to transfer heat directly from the flue gas to the organic fluid of the ORC system and to develop new heat conductor and anticorrosive materials. These aspects will be completed by the design and modelling of a new integrated monitoring and control system.

The **Exergyn Drive** (H2020) addresses the use of low-grade waste heat of <120ºC, usually 80º-95ºC from power production and its conversion into power. It can be produced at low-cost and can be sold profitably to a mass-market on a compelling commercial basis (3-year payback). This project will allow Exergyn to reach TRL9 and to be ready to produce and comercialise up to 35 x 10kW Exergyn Drives™ per month. The closest competitor-technology is the ORC.

Carbon-neutral, Low Emission Gas Turbine using Steam Injection (Clean-GT) Climate-KIC project aims to develop ultra-wet gas turbines as a commercially viable tool for domestic and large scale power generation. As well as increasing turbine efficiency, this innovative technology has the potential to be driven by alternative fuels and reduce carbon emissions significantly. There is a growing necessity and demand for power produced from a variety of new energy sources, including wind power generated hydrogen, syngas from gasification, and biofuels.

4.4.2 Torrefaction: EU and SET Plan projects

A number of 5 projects have been identified as addressing the research on biomass torrefaction, of which 3 project under FP7 and 3 project under H2020 RTD EU programmes. The **SECTOR** (FP7) project aimed to achieve market introduction of torrefaction bioenergy carriers (solid pellets), by taking the technology to pilot scale and beyond. The project focus was the development of torrefaction and densification for a broad feedstock range (clean woody biomass, forestry residues, agro-residues). The project focussed on the development, quality assurance and standardisation of dedicated analysis and test methods. Torrefied materials and the process have been optimised and characterisation tests were conducted to evaluate the necessity for new standards.

The **PYROCHAR** (FP7) project aimed to develop an economically and environmentally sound solution for the treatment and disposal of their sewage sludge from small municipalities. The PYROCHAR process has been developed a process to convert the sewage sludge into useful charcoal (or biochar) from pyrolysis and synthetic gas (or syngas) which is converted into electricity via a gas engine. The system dries the dewatered sludge and then uses pyrolysis to convert it into char and gas by-products.

The objective of **SteamBio** (H2020) is to demonstrate a mobile concept enabling pre-treatment of agro-forestry residues through superheated steam processing. A mobile demo unit (500 kg/h) will be operated at different locations to torrefy different agro-forestry residues to allow for seasonal fluctuations in the composition of the materials being valorised. The torrefied biomass fractions (solid and liberated volatiles) will then be validated as green building blocks in commercial chemical production and bioenergy use.

Torero (SET-Plan flagship project) will demonstrate a cost-, resource-, and energy-efficient technology concept for producing bioethanol from wood waste feedstock, fully integrated in a large-scale steel mill. Wood waste is converted to biocoal by **torrefaction** and biocoal replaces coal in a steel mill blast furnace, carbon monoxide in blast furnace exhaust gas is microbially fermented to bioethanol.

The **TORR** project concerns a torrefaction plant in Vägari, Estonia, for the production of 160 kt/year of bio-coal from local woody biomass. The project includes a biomass gasification CHP unit to provide heat and power. The technology will use cheaper, low quality feedstock to produce an intermediate product with a high calorific value and good transport, storage and usage characteristics in energy and liquid fuels production and chemical industry. The operational phase will start in 2019. The project is funded by the NER300 funding programme, having a total investment of €25 million.

4.4.3 Pyrolysis: EU and SET Plan projects

A number of 16 projects have been identified as addressing the research on biomass pyrolysis, of which 8 projects under FP7 and 8 projects under H2020 RTD EU programmes. The **ENV-BIO** (FP7) project aimed to develop advanced thermochemical processes (combustion, gasification and pyrolysis) for energy valorisation of biomass. The actions proposed will lead to the development of advanced technologies that are efficient, cost effective and environmentally sound. Marketing opportunities of thermochemical technologies and the environmental assessment were examined.

The **PYROGAS** (FP7) project relies on integrating biomass pyrolysis and gasification for heat and power. The feedstock is converted through pyrolysis into biochar that is then separated as a valuable product. The mixture of condensable gases from pyrolysis is introduced to a fluidised bed to convert a second feedstock to a gas through gasification process of this feedstock to power internal combustion engines to produce power & heat.

The **MICROFUEL** (FP7) project aims at developing a mobile pre-commercial microwave fast pyrolysis prototype to process forest residue and wood waste on location to bio-oil and charcoal. Bio-oil is usable as alternative to fossil fuels in boilers, engines and gas turbines. The prototype produced bio-oil and biochar in batch mode from wood chips. Continued development is expected to deliver optimised materials and systems, monitoring and control.

BIO-GO-For-Production (FP7) addresses the application of nanocatalysis to sustainable energy production in fuel syntheses. BIO-GO develops advanced nanocatalysts to realise modular, integrated processes for the production of fuels from bio-oils and biogas. Principal objectives are to develop new designs, preparation routes and methods of coating nanocatalysts on innovative micro-structured reactor designs, enabling compact, integrated catalytic reactor systems.

Biomasses and plastics were used for production of fuels in the **BIOFUEL** (FP7) project. Production of bio-oil will be carried out by one-step and two-step pyrolysis systems using various catalysts. The variance of the composition of bio-oil will be assessed from the point of the composition and fuel characteristics. Catalytic gasification of biomass/plastics and biomass-derived tar were investigated using steam as a gasification agent. Different techniques for production of bio-fuel and chemicals from biomass and plastic wastes as renewable sources were investigated.

BioEcoSIM (FP7) will valorise livestock manure to produce sustainable soil improving products (P-rich biochar). The project will combine superheated steam drying and non-catalytic pyrolysis to convert carbon in manure into P-rich biochar and syngas, with electrolytic precipitation of struvite and calcium phosphate and selective separation and recovery of NH_3 by gas-permeable membrane. Energy required in-process will be generated through combustion of syngas.

BIOBOOST (FP7) developed conversion methods to produce bio oil, biochar or slurry from biomass. BIOBOOST investigated the conversion of residues and waste to intermediate energy carriers by fast pyrolysis, catalytic pyrolysis and hydrothermal carbonisation. The project aims to perform techno-economic, social and environmental assessments of the entire supply chain. The use of energy carriers is investigated in applications of heat/power, synthetic fuels & chemicals and biocrude for refineries. Promising pathways were demonstrated over the whole chain.

The objective of **ECOCAT** (H2020) project is to investigate and improve the economics of the catalytic pyrolysis of biomass by reduction of catalyst-related operating costs and optimization of catalyst selectivity. To address the shortcoming associated with the use of zeolites as catalysts, an experimental procedure will be developed for the systematic study of mesoporosity through assessment of catalyst performance, such as activity, selectivity, coke suppression and deoxygenation.

The **FLEXI-PYROCAT** (H2020) project goal is to develop a fully flexible, integrated pyrolysis and catalyst technology to treat waste plastics to produce high value hydrogen, carbon nanotubes, chemicals or gasoline, through control of the waste pyrolysis process conditions and the use of novel designable catalysts. Extending the project to include biomass wastes further maximises the flexibility of the technology enabling a range of polymeric waste materials to be assessed for the production of high value products

Heat-to-Fuel (H2020) project will combine FT and APR technologies for the efficient production of next generation biofuels. Heat-to-fuel aims will be met thanks to the diversification of the feedstock for biofuels production, reducing the supply costs and upgrading the efficiencies of promising and flexible conversion. The large organic wastes (from HTL or other streams) can be treated with APR to produce H_2. Both dry and wet organic wastes can be integrated, with mutual advantages, i.e. steam production for gasification, HTL and APR preheating; FT heat cooling.

PYROCHEM (H2020) aims to improve the understanding of fast pyrolysis mechanisms and the process and design of reactors. It will use integrated experimental and computational approach to provide molecular-level insights into pyrolysis chemistry by following the fate of 13C labelled biopolymers. Empirical and mechanistic models will be combined to develop a new kinetic model of fast pyrolysis. This project will facilitate the commercialization of fast pyrolysis via the optimization of bio-oil yields and quality.

The overall objective of **Residue2Heat** (H2020) is to enable the utilization of ash-rich biomass and residues in residential heating applications (20-200 kWth). In this concept, various agricultural and forestry residue streams are converted into a liquid energy carrier at a scale of 15-30 MWth using the fast pyrolysis process. The fast pyrolysis bio-oil is distributed to a large number of residential end-users. Residue2Heat will perform the modification of existing condensing boilers and low emission blue-flame type burner to enable the use of the fast pyrolysis bio-oil.

Bio4Products (H2020) will apply a short thermal treatment at elevated temperature enabling the fractionation of biomass, keeping the key chemical functionalities in separate, depolymerized fractions. The process will be demonstrated in a 3 t/d demo-plant. Bio4Products will demonstrate the use of the resulting intermediate processing streams for the production of wood preservation products, furanic resins, phenolic resins and roofing material as cost-effective alternatives for fossil resources (30-100% substitution).

TO-SYN-FUEL (H2020) will demonstrate the conversion of organic waste biomass (sewage sludge) into biofuels. The project implements an integrated process combining Thermo-Catalytic Reforming, with H_2 separation through Pressure Swing Adsorption (PSA), and hydro deoxygenation (HDO), to produce gasoline and diesel substitutes and H_2. This project will be the platform for deployment of a later commercial facility processing up to 2100 tonnes/y of sewage sludge into 210,000 litres of liquid biofuels and up to 30,000 kg of green H_2.

The **bioliq**® (SET-Plan flagship project) of the Karlsruhe Institute of Technology (KIT) is based on thermochemical processes for production of chemical energy carriers from biomass (cereal straw or forestry residues). The pilot plant was built in 2005 with support by the BMEL, the FNR and the state of Baden-Württemberg. The process entails the use of fast pyrolysis for energy densification; pyrolysis char and oil are mixed to obtain a slurry (biosyncrude). Syngas production is achieved at pressures up to 80 bar by entrained flow gasification. The integrated process chain allows the production of biofuels, and synthesis gas and bulk chemicals.

The **Empyro** is a SET-Plan flagship project with the aim to build and demonstrate a 25 MWth polygeneration pyrolysis plant to produce electricity, process steam and fuel oil from woody biomass employing the BTG-BtL pyrolysis process. Oil is the main product; non-condensable pyrolysis gases are combusted to generate steam and power. The project also aims at developing and demonstrating the recovery of acetic acid from the aqueous organic acid solution that is produced through pyrolysis. The EU Empyro project was successfully concluded in 2015. The Empyro pyrolysis plant is operational and produces pyrolysis oil on a daily basis.

The **CHP Biomass pyrolysis** project involves the construction of a full-scale pyrolysis oil plant using 100,000 t wood chips, linked to the existing Jelgava CHP plant in Latvia. The plant capacity of bio-oil is about 40,000 t (160-180 GWh of fuel). The devolatilized compounds are condensed into bio-oil and the remaining solids, including sand and fuel char, are returned to the FB boiler to produce heat and electricity. The bio-oil will replace heavy fuel oil. The operational phase will start in 2020. The project is funded by the NER300 programme, with a total investment of €3.9 million.

The **Fast pyrolysis** project aims the construction of a full-scale pyrolysis oil plant 130,000 t woodchips, at the Pärnu CHP plant in Estonia. Annual output of pyrolysis oil is expected to be 50,000 t (about 200-220 GWh) fuel, that will replace heavy fuel oil in power plants. The devolatilized compounds are condensed into bio-oil and the remaining solids, including sand and fuel char, are combusted together with non-condensable gases to produce heat and electricity. The operational phase will start in 2020. The project is funded by the NER300 funding programme for innovative low-carbon technologies. The total funding investment is € 6.9 million.

4.4.4 Hydrothermal processing: EU and SET plan projects

A number of 7 projects have been identified as addressing the research on biomass torrefaction, of which 5 project under FP7 and 5 projects under H2020 RTD EU programmes. **NEWAPP** (FP7) proposed to create a continuous system to obtain high-value carbon from waste (green waste, agricultural waste, municipal solid waste, waste from food industry). NEWAPP targeted the upgrade of turning waste into new resources using HydroThermal Carbonization (HTC) process as alternative to the use of wet biomass. NEWAPP analysed the potentials of wet biomass streams for HTC and perform testing for heat recovery and efficiency for tailor-made HTC products. The project developed new knowledge about the characteristics and uses of HTC coal.

The **EUROCHAR** (FP7) project aimed to test the effectiveness of transforming biomass into biochar, for carbon sequestration and large-scale removal of GreenHouse Gases (GHG) from the atmosphere with great potential for carbon sequestration. The project performed tests on different biochar production methods, conducting field trials and modelling the impact of this strategy. EUROCHAR tested two different methods to create biochar: gasification or thermal carbonisation, and hydrothermal carbonisation, obtaining biochars with no toxicity to plants. Biochar was produced from different agricultural products for subsequent detailed analyses and a set of coordinated field studies.

Heat-to-Fuel (H2020) project will combine FT and APR technologies for the efficient production of next generation biofuels delivering higher fuel qualities and reduced GHG reductions. Heat-to-fuel aims will be met thanks to the diversification of the feedstock for biofuels production, reducing the supply costs and upgrading the efficiencies of promising and flexible conversion. The large organic wastes (from HTL or other streams) can be conveniently treated with APR to produce H2. Both dry and wet organic wastes can be integrated, with mutual advantages, i.e. steam production for gasification, HTL and APR preheating; FT heat cooling without external utilities.

The objective of **HTC4WASTE** (H2020) project is to demonstrate, at full scale, the Hydrothermal Carbonisation (HTC) technology as a flexible organic waste recovery technology, suitable for converting organic waste streams into carbon-neutral biocoal, fertility products, water, and energy. A full-scale HTC installation will be built to demonstrate its economic and technological performance across a range of waste streams with difficult characteristics. The demo will target at least three market applications (sewage sludge, food waste and animal by-products and spent mushroom compost) on a commercial scale (10000 tonnes/year).

The **Hydrofaction** (H2020) project aims to develop the Steeper Energy Aps (SEA) innovative hydrothermal liquefaction technology platform: HydrofactionTM. The project will bring Hydrofaction to market via testing, scale-up and demonstration. Hydrofaction oil can be burned in CHP applications, used a substitute for low-sulphur marine diesel or may be upgraded to diesel or jet via traditional petroleum refineries. The scaled demo plant, about 100 times larger than SEA's current pilot facility or 5000 tonne capacity.

The objectives of **HyFlexFuel** (H2020) project include advancing and demonstrating HTL conversion from diverse biomass feedstocks and increasing heat integration and product recovery. The project also aims at understanding of relation between feedstock and process conditions vs. product yield and quality and efficient valorisation of residual process streams. The project will also target the quantification of technology gaps of a full-scale production plant and the techno-economic and environmental performance potentials, risks and benefits potential.

The **NewCat4Bio** (H2020) project focused on the preparation, characterization and application of (hydro)thermally stable, homogeneous, and porous metallosilicate catalysts. Non-hydrolytic sol-gel routes will be applied since they produce materials with high homogeneity and they allow the one-step functionalization of the oxides surface. The project will focus and demonstrate the synthesis of alumosilicates, and then broaden the work to Zr-, Ti-, Nb-, and Ta-doped silicates. Advanced analytic techniques will be used for the characterization of heterogeneous catalysts.

The **bioCRACK** pilot plant (SET-Plan flagship project) with a biomass capacity of $100\,kg\,h^{-1}$ is based on the liquid phase biomass pyrolysis in vacuum gas oil and converted into gaseous, liquid and solid products. The process generated pyrolysis gas, pyrolysis oil, biochar, gasoil and kerosene, naphtha and vacuum gas oil. The bioCRACK process is the first technology for direct biomass liquefaction integrated in an oil refinery. This process has so far been practised in pilot scale, the next step would be a demo plant. The BioCRACK gasoil, kerosene and naphtha were used in hydrogenation to produce gasoline and diesel.

Waste-to-Fuel (W2F) process from the plant in **Gela** (SET-Plan flagship project) is able to transform the organic part of urban waste through liquefaction into bio-oils that are used for the production of energy or fuels. One tonne of organic matter produces up to 150 kg of bio-oil. The aqueous phase is treated to be used for irrigation or industrial purposes and biogas. The construction of a green refinery will lead to the conversion of the Gela refinery in a biorefinery (750k tonnes/year). The conversion will make use of the Eni proprietary ecofining technology, that enables the production of green diesel. The Gela plant is planned to start operating in 2018.

4.4.5 Biomass gasification: EU and SET Plan projects

A number of 19 projects have been identified as addressing the research on biomass gasification, of which 14 projects under FP7 and 5 projects under H2020 RTD EU programmes. The **GREENSYNGAS** (FP7) project key goal was the development and demonstration of a novel, advanced syngas cleaning technologies using both chemical and physical methods in order to reduce impurities from the gasifier's product gas to limits the requirements for upgrading to syngas in the production of vehicle fuels. The first used physical removal of tars and another utilised catalytic reforming of the tar contaminants. A third system employed oxidative thermal treatment.

The **ENV-BIO** (FP7) project aimed to develop advanced thermochemical processes (advanced combustion, gasification and pyrolysis) for the energy valorisation of biomass. The actions proposed will lead to the development of advanced technologies in the use of biofuels that are efficient, cost effective and environmentally sound. Marketing opportunities of thermochemical technologies and the environmental assessment were examined.

The **UNIQUE** (FP7) project aimed to develop a compact, multi-functional reactor delivering high-purity syngas for small to medium-scale power plants. Fluidised-bed gasification was integrated with hot gas cleaning and conditioning in one system fitted with novel catalytic filters, which remove tars, particulate matter and other chemicals, proved in laboratory- and pilot-scale tests. Using tar-reforming catalytic filter systems, UNIQUE manufactured commercial-size catalytic ceramic candle filters tested at bench scale, removing more than 99 % of particulate matter.

The **PLAGASMIC** (FP7) project developed and tested a microwave plasma reactor for converting animal waste to biogas. The prototype microwave plasma reactor uses multiple of low-energy microwave sources to gasify animal manure and produce syngas. An electrocoagulation filtration system was incorporated into the reactor to remove waste products from the remaining liquid after gasification.

The **INORGASS** (FP7) project researched the distribution and environmental risks of a series of inorganic components into the gas phase, char residue and condensate, from sewage sludge gasification. An experimental study had to be performed on bench scale, including advanced and complimentary chemical analyses, both on-line and off-line (GC-TCD, FTIR, ICP-AES, X-ray microfluorescence, X-ray diffraction and elemental analysis).

The **GASPRO-BIO-WASTE** (FP7) project developed an instrument able to analyse biomass and waste gasification processes over a broad temperature and pressure range. Several in situ high-temperature sensors able to measure various properties of the produced gas were developed. The sensors form part of a lab-scale gasification process analyser, along with a gravimetric analyser and a gas refinery unit. The refinery unit tests different kinds of gas treatments for their ability to reduce or remove dangerous components from the gas before entering the power generator.

EUROCHAR (FP7) aimed to test the effectiveness of biomass conversion into biochar, for carbon sequestration and GHG removal from the atmosphere. The project performed tests on different biochar production methods, conducting field trials and modelling the impact . EUROCHAR tested two different methods to create biochar: gasification or thermal carbonisation, and hydrothermal carbonisation, obtaining biochars with no toxicity to plants. Biochar was produced from different agricultural products for subsequent detailed analyses and a set of coordinated field studies.

The **GAS BIOREF** (FP7) project aimed to demonstrate the use of a range of feedstocks (solid recovered fuel, derived from MSW and biomass from energy crops) to electricity and heat in a Bubbling Fluidized Bed gasification plant. The project aims to demonstrate coupling of two different fuel supply chains (energy-crops and SRF), in a medium-scale co-generation plant (fuel input 13.5 MW).

The **POLYSTABILAT** (FP7) project aims to demonstrate a novel gasification plant using a fuel (Stabilat) derived from a Municipal Solid Wastes recycling plant. The produced gas will be cleaned in a novel high temperature gas filter and combusted in a gas boiler coupled with a 0.5 MWe steam turbine. The integrated facility will provide a sustainable solution for the treatment of MSW and generate energy.

PHENOLIVE (FP7) intends to revalorize the residue generated by the olive oil process (wet olive pomace) by extraction of polyphenolic compounds using pulsed electric field as an alternative to conventional chemical extraction techniques based on the use of organic solvents. Steam gasification of the resulting solid waste will recover electricity and heat for the whole process.

The **PYROGAS** (FP7) project relies on integrating biomass pyrolysis and gasification for heat and power. The feedstock is converted through pyrolysis into biochar that is then separated as a valuable product. The mixture of condensable gases from pyrolysis is introduced to a fluidised bed to convert a second feedstock to a gas through gasification process of this feedstock to power internal combustion engines to produce power and heat.

This **RENEGAS** (H2020) project deals with an advanced downdraft gasification system using bio-waste to produce clean and high quality synthetic gas using a syngas cleaning and cooling which ensures that its product gas is ultra-clean that can be used for electricity and heat generation. The project will develop a feasibility study and business plan as a roadmap for scaling-up and market replication, by addressing policy and market analysis and local feedstock analysis, production scale-up and sales strategy development.

Biomasses and plastics were used for production of fuels in the **BIOFUEL** (FP7) project. Production of bio-oil was carried out by one-step and two-step pyrolysis systems using various catalysts. The variance of the composition of bio-oil was assessed from the point of the composition and fuel characteristics. Catalytic gasification of biomass/plastics and biomass-derived tar were investigated using steam as a gasification agent. Different techniques for production of bio-fuel and chemicals from biomass and plastic wastes as renewable sources were investigated.

The **POLYSTABILAT** (FP7) project aims to demonstrate a novel **gasification** plant using a fuel (Stabilat) derived from a Municipal Solid Wastes recycling plant. The produced gas will be cleaned in a novel high temperature gas filter and combusted in a gas boiler coupled with a 0.5 MWe steam turbine. The integrated facility will provide a sustainable solution for the treatment of MSW and generate energy.

The **UNIfHY** (FP7) project aims to obtain continuous pure hydrogen production from biomass by integration of advanced biomass steam gasification and syngas purification processes. UNIQUE coupled gasification and gas conditioning technology, water-gas shift and pressure swing adsorption system. The result will be two prototype units up to 500 kg/day. The project aimed to achieve conversion efficiency in hydrogen above 70%, a reduction of the gas conditioning cost to 30% of a standard system, investment cost savings more than 50%, and a hydrogen production cost below 4€/kg.

The **H2-IGCC** (FP7) project aimed to provide and demonstrate technical solutions for the use of gas turbines in IGCC plants, able to use hydrogen-rich syngas derived from a pre-combustion CO2 capture process. The project addresses the issues of combustion, hot gas path materials, the aerodynamic performance, and system analysis. The project also looks into turbine fuel flexibility, which will be demonstrated to allow the burning of back-up fuels, such as natural gas.

HiEff-BioPower (FP7) planned to develop a highly efficient biomass CHP technology for a capacity of 1 to 10 MW, consisting of a fuel-flexible fixed-bed updraft gasifier, a novel compact gas cleaning system and a Solid Oxide Fuel Cell (SOFC). The technology will be able to use a wide fuel range (wood pellets, wood chips, SRC, agro-pellets, fruit stones/shells). The system consists in fuel-flexible updraft gasification with ultra-low particulate matter and alkali metal concentration, an integrated high temperature gas cleaning and a SOFC system which tolerates certain tar amounts.

The **FLEDGED** (H2020) project will deliver a process for bio-based dimethyl ether production from biomass, combining a flexible sorption enhanced gasification process and DME synthesis process. The primary aim is to develop a highly intensified and flexible process for DME production from biomass and validate it in industry. The plant will be able of producing syngas with tailored composition by adapting the SEG process parameters, which allows coupling with an electrolysis system for converting excess renewable electricity into a high value liquid fuel.

The **FlexiFuel-SOFC** (H2020) project aims at the development of an innovative, efficient and fuel flexible micro-scale biomass CHP consisting of a small-scale fixed-bed updraft gasifier (5 to 150 kW), a compact gas cleaning system and a Solid Oxide Fuel Cell (SOFC). This entails an up-draft gasification with ultra-low particulate matter and alkaline concentrations, which reduces the need for gas cleaning, an integrated gas cleaning for dust and HCl removal, desulphurisation and tar cracking as well as a SOFC system. This is expected to reach high gross electric (40%) efficiencies.

The **FlexiFuel-CHX** (H2020) project aims at the development of a new fuel flexible and highly efficient residential biomass heating (TRL of 5) technology (20 - 130 kW) focused on highly efficient and fuel flexible residential heat production at almost zero CO and OGC emissions, by 50% reduced NOx emissions (compared with conventional boilers) as well as ultra-low PM emissions below 13 mg/MJ. It is based on the UleWIN wood chip and pellet boiler concept consisting of a fixed-bed updraft gasifier directly coupled with a Low-NOx gas burner and a hot water boiler.

The **Guessing gasifier** (SET-Plan flagship project) is based on the Fast Internally Circulating Fluidized Bed (FICFB) gasification system, developed by the Institute of Chemical Engineering (Technical University of Vienna) and by AE Energietechnik in Austria. The pilot plant has a fuel capacity of 8 MW and an electrical output of about 2 MWel. The plant is based on high-temperature gasification in dual-fluidised bed to synthesis gas and downstream processing including different routes to gases, liquids and chemicals (e.g. methanation, Fischer-Tropsch synthesis).

The **Gaya** (SET-Plan flagship) project aims to demonstrate a pathway for gasification and methanation of residues (e.g. wood, straw) to produce biomethane. This involves a catalytic process that converts synthesis gas into methane at around 400°C. Gaya is a cutting-edge technology platform, with the goal to enable the production of biomethane through biomass-to-gas concept, which can be transmitted via the current networks or can be used directly for Natural Gas Vehicles (NGV). The plant has a €47 million budget, including €19 million as subsidies from ADEME.

The **GoBiGas** (Gothenburg Biomass Gasification) (SET-Plan flagship) project, started in 2005, based on a 32 MWth dual fluidized bed (DFB) gasifier (150 dry tonnes of biomass/day), and Synthetic Natural Gas (SNG) synthesis, producing up to 20 MW of biomethane. It is a first-of-its-kind plant the production of advanced biofuels from woody biomass (methane). A research program with a 2–4-MW (10–20 dry tonnes of biomass/day) DFB gasifier was established in 2007 at Chalmers University of Technology. The project has acquired experience from around 10,000 h of operation of the demo plant and more than 25,000 h of operation of the research gasifier.

The **Ambition** (SET-Plan flagship) project aims to develop an innovative concept, which include pre-treatment, gasification, gas cleaning and conditioning and syngas fermentation. Biomass pre-treatment will be based on non-hazardous catalysts and/or green solvents to enable the reduction of the production of fermentation inhibitors and the need of hydrolytic enzymes for hydrolysis. The project will adapt the gasification technology for improved high-added-value carbon utilization and proper H_2/CO ratios for downstream syngas processing. The final goal is the combination and integration of a thermochemical and a biochemical processs into an overall process design.

AMBIGO is a SET-Plan flagship initiative based on thermochemical conversion (gasification) for producing 3 000 m^3/h of SNG from waste in Alkmaar. Gas from gasification (MILENA technology) has already been tested on a smaller scale at ECN in the Netherlands (25 KW and 0.8 MW) and in India (4 MW). Through washing the gas with a scrubbing oil, tar particles will be removed and used as fuel in the gasification process (OLGA technology), already tested on a smaller scale at ECN in the Netherlands (5 KW and 0.8 MW) and in France, Portugal and India (4 MW each). The energy carriers (mainly CO and H_2) are converted, in a several stages, to methane (ESME technology).

The aim of the **COMSYN** (SET-Plan flagship) project is to develop a new BTL concept based on distributed conversion of biomass residues to intermediate liquids in small-to-medium scale (10-50 kt/y) units. The process involves gasification in dual fluidized bed, gas filtration, steam reforming of tars and hydrocarbons and conversion to hydrocarbons suitable for gasoline, diesel and jetfuel production through Fischer-Tropsch synthesis. The primary conversion will be integrated with heat and power production, resulting in 80 % efficiency of biomass utilization. The produced FT-wax will be transported to a large-scale oil refinery, which will be converted into biofuel refinery.

The **Ajos** BTL (NER 300) project is based on gasification of forest biomass and through FT-synthesis. The project is funded by the NER300 funding programme for innovative low-carbon technologies. The plant is located in Ajos, Finland and it will produce up to 225 000 tons of biofuels and use approximately 1.8 million tons of biomass annually. The operational phase will start in December 2018. The total funding investment is EUR 88.5 million.

The **Bio2G** project, funded by the NER300 funding programme, aims to demonstrate the large-scale production of 200 MWh renewable gas in Landskrona or Malmö, Sweden, for injection in the gas grid using forest residues, stumps, fuel wood, recycled and short rotation wood. Gas production is based on pressurized fluidized bed gasification with oxygen. Cleaned gas, obtained by breaking down hydrocarbons chains, in a tar reformer at high temperature, is converted to methane in adiabatic reactors. Excess heat is used to provide electricity for the plant and heat to district heating. The operational phase will start in 2020. The total funding investment is €203.7m.

GoBiGas (Gothenburg Biomass Gasification Project) of Göteborg Energi, Sweden, is a first of a kind plant for industrial scale SNG production. The Project will demonstrate the large-scale conversion of low-quality wood into SNG by indirect gasification at atmospheric pressure, gas cleaning, methane production, pressurization and injection into the gas network. The plant uses ~0.5 Mt/year forestry feedstock, including pulpwood and forest residues to produce 160 GWh/year of SNG. The GoBiGas facility has started in 2014. GoBiGas will receive €58.8m funding under the NER300 programme. In a bid to reduce the financial impact, the plant was put up for sale in 2017; no other investor was found and the owner decided to terminate the project in advance in 2018.

Table 8. Selection of R&D gasification plants worldwide

Project Owner…	Project name	Country	TRL	Outputs
Bio SNG Guessing	Synthesis Demo Guessing	Austria	TRL 6-7	576 t/y SNG
SynCraft	CraftWerk Schwaz	Austria	TRL 4-5	0.1 Mwel power +0.5 MWth
urbas Energietechnik	CHP Demonstrationsanlagen URBAS	Austria	TRL 6-7	0.15 Mwel power +0.3 MWth heat
Enerkem	Synthesis Enerkem Sherbrooke	Canada	TRL 4-5	375 t/y ethanol +475 m3/y methanol +SNG
EP Engineering ApS	Helufsholm CCG - phase A	Denmark	TRL 4-5	0.4 MWe power
Sindal District Heating Company	Dall Energy CHP plant in Sindal	Denmark	TRL 8	0.8 MWel power +5 MWth heat
Volter	Kempele Ecovillage	Finland	TRL 4-5	0.03 MWel power
VTT	Pressurized FB for synthesis gas	Finland	TRL 4-5	0.5 MWth heat
VTT	Dual fluidized-bed steam gasification pilot	Finland	TRL 4-5	0.35 MWth heat
GDF Suez + consortium	Gaya	France	TRL 1-3	0.1 t/y SNG
Agnion Technologies GmbH	CHP Agnion Biomasse Heizkraftwerk Pfaffenhofen	Germany	TRL 4-5	6.1 MWel power +32.5 MWth SNG
CHOREN Industries GmbH	CHOREN plant Freiberg	Germany	TRL 4-5	53 t/y FT liquids
Wegscheid Demo	Wegscheid Demo	Germany	TRL 6-7	0.125 MWel power +0.23 MWth heat
SEK Koblenz	KSV Koblenz	Germany	TRL 8	0.33 MWel power +0.39 MWth heat
ZAB Balingen	KSV Balingen	Germany	TRL 8	(0.46 MWth heat
ECN	MILENA Gasifier	Netherlands	TRL 4-5	200 m3/h clean syngas
HoSt	CFB Tzum	Netherlands	TRL 6-7	3 MWth heat
Chalmers Technical Univ.	Centre for Indirect Gasification of Biomass	Sweden	TRL 4-5	4 MWth heat
PEGB	SP ETC	Sweden	TRL 4-5	1 MWth heat
Goteborg Energi AB	GoBiGas	Sweden	TRL 8	11,200 t/y SNG
Cortus Energy AB	Probiostal	Sweden	TRL 8	6 MWth heat
Emamejeriet AB	Emamejeriet (Ema dairy)	Sweden	TRL 8	0.04 MWel power +0.1 MWth heat
VVBGC AB	Vaexjoe Vaernamo Biomass Gasification Center AB	Sweden	TRL 6-7	6 MWel power +8 MWth heat+1,000 m3/h syngas
TUBITAK	Synthesis TUBITAK MRC Kocaeli	Turkey	TRL 4-5	0.2 MW SNG
Advanced Plasma Power Ltd	BioSNG pilot plant	UK	TRL 4-5	0.06 MWel power +4 kg/h SNG
Go Green Fuels Ltd	GoGreenGas	UK	TRL 8	1,500 t/y SNG
Southern Research Institute	Tech dev lab & pilot plant	US	TRL 4-5	0.002 t/y FT liquids +alcohols+power
INEOS New Planet BioEnergy	INEOS Plant Vero Beach	US	TRL 4-5	6 Mwel power +3.469 m3/h ethanol

Source: ETIP, 2018.

4.5 Algae for bioenergy: EU and SET Plan projects

A number of 32 projects have been identified as addressing the research on algae production for energy production, of which 12 projects under FP7 and 20 projects under H2020 RTD EU programmes. The **AT~SEA** (FP7) project aimed to develop advanced technical textiles to demonstrate the technical and economical feasibility of open sea cultivation of macroalgae. AT~SEA targets the development of innovative offshore textile products to stimulate bio-energy production from seaweed by enabling open sea large scale cultivation and harvesting.

The **ALGAENET** (FP7) project investigated the use of sunlight to enhance biogas production from AD processes. Sunlight was used in the production of microalgae and an anaerobic bioreactor will be used to convert the biomass into biogas. Carbon dioxide and the nutrients released during anaerobic conversion will be used for microalgae production. A multi-disciplinary approach was used on the cultivation and harvesting of microalgae, and the production of biogas and hydrogen.

DOP-ECOS (FP7) focussed on bioprocesses that couple a photobioreactor, where microalgae use sunlight to produce biomass, and an anaerobic digester, where bacteria convert biomass into biogas and recover nutrients. It aims to optimize the design and operation of integrated microalgal / bacterial system and to develop the methods and tools for their reliable analysis and optimization.

The **SUNBIOPATH** (FP7) project aims to improve the biomass yield of Chlamydomonas reinhardtii and Dunaliella salina green microalgae. Researchers investigated the photochemistry and sunlight capture process and biochemical pathways and mechanisms that influence ATP synthesis. Optimal growth and photoconversion efficiency of selected mutant strains in photo-bioreactors was assessed. The project will help provide new solutions for the valorisation of microalgal biomass, through genetic engineering of chloroplast and biomethane production.

The **SOLALGEN** (FP7) project aimed to build a low-cost light collection and distribution system for increasing algae production. Research focused on a light/optical system, which was installed on both the photobioreactor and open pond units. Hybrid open pond photobioreactors were developed that exploits the advantages of both methods of algal cultivation and parallel experiments were conducted in order to determine the impact on production unit yield.

The **ALGAEMAX** (FP7) project used acoustic standing waves for harvesting high-quality microalgae biomass from their water-based growth medium. ALGAEMAX designed and built two prototype ultrasound flow cells which were validated on a small scale using models and synthetic particles and then tested under different conditions with real algal cultures.

The **GIAVAP** (FP7) project was established to improve and genetically transform algae to reduce algal production costs. The project genetically engineered seven microalgae species to make them better suited to specific growth conditions for the commercial production of biomaterials and improved the production of fatty acids, carotenoids and high-value proteins. Large-scale cultivation, harvesting and extraction techniques were adapted and applied to microalgae species and algal biomass and purified bioproducts were tested in various model systems.

The **OPERATION SWAT** (FP7) project objective was to develop an algae harvesting technology that would yield 95 % recovery at 40 % lower costs. The project studied the characteristics and particle size of seven microalgae species to identify the correct filters and investigated 20 different flocculating agents to improve the filtration. Two prototype systems were designed and installed in different microalgal production facilities. The final prototype, operated continuously, could remove 97% of suspended solids.

The **HARVEST** (FP7) network provides training opportunities for young researchers in key aspects of molecular biosciences and biophysical sciences. This network brings together major EU centres with expertise in a wide range of disciplines (in molecular biology, plant physiology, biochemistry, biophysics and systems biology). It aims at deeper understanding photoregulatory mechanisms in photosynthetic organisms and exploitation of knowledge.

The **ALGADISK** (FP7) project investigates the ways of producing microalgae for CO_2 capture and biomass production. The project aimed to develop a modular, scalable and automated biofilm reactor to produce algal biomass. It identified several algal species that can be grown on a coated surface with higher yields and lower costs. A successful biofilm growth of selected microalgae was achieved in the lab-scale reactor and a harvesting technology for biofilms was designed and tested at lab-scale.

BIOFAT (FP7) was a demo project for microalgae cultivation (10 ha), with a target of 100 tons/ha to develop the concept of algorefinery. The project included two stages: process optimization in two pilot facilities, 0.5 ha each, in Italy and Portugal and scale-up to a 10 ha demo facility. The project built and operated photo bioreactors for inocula and raceways for algae production. Pre-concentration and centrifugation were tested for harvesting followed by extraction by mechanical cell disruption and conversion to diesel by trans-esterification and to ethanol through fermentation.

ALL-GAS (FP7) was established to demonstrate the production of biofuels from microalgae at large scale (10 ha site). Several processes were investigated: oil extraction and digestion of residual algae together with wastewater solids to produce biogas. Wastewater and nutrients were re-used to stimulate algae growth. The biogas was purified and compressed to serve as vehicle fuel. To reach the enhanced algal yield, additional CO_2 was used from the biomass combustion (sludge from wastewater treatment, digestate from residual algae and wastewater solids) needed for drying.

The **ECO-LOGIC GREEN FARM** (H2020) project addresses a production plant integrating algae cultivation in photobioreactors with a syngas CHP as a source of carbon for the microalgae photosynthesis. Market application includes biomass for combustion and for AD, food supplements, pharmaceutical /cosmetics products and fertilizers. The work includes a pilot line for microalgae production, including photobioreactor for research on bio-lighting algae and continues with pilot production, performance verification and market replication.

The **CMHALGAE** (H2020) project aimed to create a bio-based and re-usable Cellulose Magnetic Hybrid (CMH) nanomaterial for downstream microalgae processing. The CMH nanomaterial will be capable of combined flocculation, dewatering and cell disruption of microalgae and can be removed and re-used. The techno-economic feasibility of this technology will be demonstrated in two model systems. This CMH nanomaterial would be able to achieve a critical cost reduction in microalgal downstream processing and advance large-scale microalgae production towards commercialization.

The **PHARM AD** (H2020) project will address the threat of micropollutants in the form of pharmaceutical residues (PR). The approach include the investigation of the efficacy of AD for the removal of PRs in conventional treatment of sludges, but also on the novel application of AD to the direct treatment of wastewaters rich in these pollutants (e.g. hospital or industry). It will also try to combine PR removal by AD with biological nutrient removal (nitrogen) by micro-algae cultivation, thus addressing one of the drawbacks of AD: the lack of nitrogen removal.

The **MONSTAA** (H2020) project will develop new varieties of microalgae from Arctic and Antarctic environments and study their metabolism in low temperature bioreactors. The research outcomes will be: genome-scale characterization of new varieties of microalgae; development of novel bioprocesses for high yields of lipids, proteins and carbohydrates in cold climates predictive metabolic models for maximizing yields of products in non-model varieties of microalgae.

The **BIOMIC-FUEL** (H2020) project aim the development of improved photonic materials that can be used to maximise algal growth in order to radically transform the algal biofuel sector. The specific objectives are: to explore the in vivo light field, optical properties and photosynthetic efficiency of a range of coral species from different light regimes; understand the nanophotonic and structural properties of corals underlying the optimised light modulation; and apply the biophotonic insight to design novel photonic materials for the improved growth of microalgae.

The project **ALGAE4A-B** (H2020) seeks to exploit the microalgae diversity, as a source for high-added-value biomolecules in aquaculture and cosmetics. The project will combine both basic and applied multidisciplinary research in the fields of –omics technologies, biochemistry and applied biotechnology. The project aims to develop and optimize of low input and application-based microalgae culture systems, develop of -omic resources for both microalgae and fishes; develop of downstream processing of high value added products from microalgae; develop, formulate and in vitro evaluate a new range of cosmetic and nutraceutical products for aquaculture.

The **ALGAECEUTICALS** (H2020) project will combine both basic and applied research in the fields of –omics technologies, biochemistry, applied and enzyme biotechnology in order to exploit microalgae resources for the development: natural UV sunscreens, based on algae mycosporine-like aminoacids; algae-based nutraceuticals as functional foods and food supplements; algae-derived proteases with applications in cosmetic and food industry.

The **SOLENALGAE** (H2020) project aims to investigate the molecular basis for efficient light energy conversion into chemical energy, to increase microalgae production combining the investigation of the principles of light energy conversion with bio-technological engineering of algal strains. The high algae growth potential has not been exploited yet, since biomass yield obtained up to now is relatively low, with high production costs. The main limitation is the low light use efficiency, reduced from the theoretical value of 10% to 1-3%.

IPHYC's patented WWT process uses microalgae to remove nutrients (nitrogen, phosphorus, etc.) from wastewater effluents. The process has been validated by I-PHYC in field trials at Wessex Water’s Avonmouth WWT plant. The **INDALG** (H2020) project aims to prove its technology & develop its process to commercial readiness by building a commercial demonstrator for wastewater treatment and optimising its process, to develop methods of recovering value from algae.

AlgaEnergy (H2020) reached a semi-industrial scale with the start of the first phase operations in Spain, which captures flue gas a combined cycle plant. The objective of the INTERCOME project is to validate the process in real environment developing AlgaEnergy’s production facilities from TRL7 to TRL9, overcoming the current barriers to commercialization. The project’s objective is turning a demonstration production plant into a commercial industrial facility, which is called to be the European Flagship of microalgae production facilities.

The **BEAL** (BioEnergetics in microALgae) (H2020) project aims to: characterize and compare the photosynthetic regulation modes by biophysical approaches; use genetic and biochemical approaches to gain fundamental knowledge on aerobic respiration and anaerobic fermentative pathways; and investigate and compare interconnections between respiration, photosynthesis, and fermentation in organisms. The acquired knowledge will allow exploiting the microalgae diversity in a biotechnological perspective, and remove constraints on microalgae growth.

The **ALGAMATER** (H2020) is a robust, flexible, cost-effective, and eco-friendly wastewater treatment system, currently at a prototype stage (TRL7). In pilot tests, Algamater demonstrated decreased energy costs in wastewater treatment by more than 60% and lowered operational costs by more than 40% compared to traditional wastewater treatment plants. This project will upgrade, scale up and integrate the Algamater components into a full-scale wastewater treatment plant capable of demonstrating our game-changing technology at an industrial level.

The **ECO-LOGIC GREEN FARM** (H2020) project addresses integrating algae cultivation in photobioreactors with a syngas CHP as a source of carbon for microalgae photosynthesis. The work includes a pilot line for microalgae production, including photobioreactor for research on bio-lighting algae and continues with pilot production, performance verification and market replication. Market application includes: biomass for combustion and AD; food supplements for human/animal use; pharmaceutical/cosmetics products; fertilizers.

The overall objective of **BIOSEA** (H2020) is the development and validation of innovative, competitive and cost-effective upstream and downstream processes for the cultivation of 2 microalgae (Spirulina platensis and Isochrysis galbana), and 2 macroalgae (Ulva intestinalis and Saccharina latissima) to produce and extract at least 6 high value active principles at low cost (up to 55% less than with current processes) to be used in food, feed and cosmetic/personal care as high-added value products.

The overarching aim of **ALFF** (H2020) is to train researchers and technologists targeting the development of superior mass algal cultivation and biocontrol strategies. ALFF tackles: the identification, taxonomy and utilisation of algal symbionts and pathogens; inter- and intra-species signalling and chemical ecology in aquaculture and natural environment; and harnesses state of the art genomics, molecular, and biochemical techniques to characterise these interactions.

ABACUS (H2020) aims at the development of a new algal biorefinery for high-end applications. ABACUS aims to demonstrate biorefining processes allowing valorizing up to 95% of the algal biomass into high value ingredients and by-products. ABACUS focuses on optimizing cultivation steps and mastering production by online monitoring and automated control of photobioreactors with the development of specific sensors for the relevant parameters (light, PO2, PCO2, nutrients).

VALUEMAG (H2020) project aims to provide groundbreaking solutions for microalgae production and harvesting for aquatic/marine biomass integrated bio-refineries. Production-cultivation and harvesting objectives are achieved by using magnetic nanotechnologies. Magnetic microalgae (MAGMA) are immobilized onto a soft magnetic conical surface (SOMAC) that allow optimum cultivation, enhance biomass productivity and lower costs of biomass production. Biomass is directly utilized for the production of molecules, using supercritical CO_2 extraction and a new selective magnetic separation method for precise selection of value-added products.

The overall objective of the **MAGNIFICENT** (H2020) project is to develop and validate a new value chain based on cultivation and processing, to transform microalgae into valuable ingredients for food, aquafeed and cosmetics applications. Optimization will be done: upstream, cultivation related processes via adaptation and selection of algae varieties, improvement of growing conditions and target product concentration in the cell; and downstream process (separation, extraction, purification) to maximise the production of compounds of interest.

MacroFuels (H2020) aims to produce advanced biofuels from macro-algae (ethanol, butanol, and biogas). The project will achieve advancement in the: cultivation of brown, red and green seaweed; pre-treatment of seaweed to yield sugars at relevant concentrations (10-30%); increasing the bio-ethanol production to concentration above 4%/l; increasing the bio-butanol yield to 15 g./l by through novel organisms; increasing biogas yield to convert 90% of available carbon; developing thermochemical conversion of sugars to fuels. The technology will be taken from TRL3 to TRL 4/5.

SABANA (H2020) aims at developing a large-scale integrated microalgae biorefinery for the production of various products, biofertilizers and aquafeed, using marine water and nutrients from wastewaters. The objective is to demonstrate the technology, achieving a zero-waste process at demo scale up to 5 ha. SABANA includes the scale-up of reactors, using marine water to recover nutrients from wastewaters, develop harvesting processes, establish processes for bioproducts extraction, process residual biomass to produce biofertilizers and aquafeed in zero-waste schemes.

The **GENIALG** (H2020) project aims to boost sustainable exploitation of two high-yielding species of seaweed biomass. GENIALG will demonstrate the economic feasibility and environmental sustainability of cultivating and refining seaweed for multiple uses. The final goal is developing a bio-refinery concept and accelerate efficient and sustainable exploitation of seaweed biomass to bring new high-value products on the market.

4.6 Biorefineries: EU and SET Plan projects

A number of 43 projects have been identified as addressing the research on biorefineries, of which 14 projects under FP7 and 29 projects under H2020 RTD EU programmes. The **BIOCORE** (FP7) project aimed to create and demonstrate a sustainable and economically viable biorefinery concept that can use multiple feedstocks. BIOCORE used an existing organosolv technology for optimising the process for several feedstocks. The project demonstrated the production of several products, including ethanol, bio-based resins for wood panels, polyurethane foams and plastics. Researchers used modelling and site analysis to design optimised product pathways for a future biorefinery.

The project **SUPRA-BIO** (FP7) was set to develop advanced and competitive biorefinery concepts that exploit biomass to produce various compounds and value-added fine chemicals in addition to biofuels. SUPRA-BIO is delivering an integrated biorefinery concept to profitably produce biofuels from organic waste.

This **EUROBIOREF** (FP7) project targeted a multi-faceted approach to the bioeconomy, involving non-edible feedstocks, multiple biochemical and thermochemical processes, as well as various industrial products. EUROBIOREF tested new oil crops and lignocellulosics and established test fields for various feedstocks. It developed a biomass supply logistics model and applied it to four crops. EUROBIOREF constructed a new pilot plant in Norway to process woody biomass and described and demonstrated five value chains for biorefineries.

The **GLYFINERY** (FP7) project focussed on the development of novel technologies based on biological conversion of glycerol by micro-organisms, into biofuels, bioenergy and biochemical, to find new uses for glycerol in an advanced biorefinery concept. The project identified the most promising biocatalytic microorganisms and the fermentation processes for biological conversion, and focussed to optimising the bioprocess design and the recovery processes.

The project **AFORE** (FP7) was set to develop bio-based solutions to isolate and upgrade natural chemicals from forest residues or process side-streams to be used for novel value-added applications. The project investigated several methods to extract and upgrade materials from both solid and liquid wood-derived samples, of which several were chosen for up-scaling and testing at pilot or industrial scale.

The **VALOR-PLUS** (FP7) addresses the realisation of closed loop integrated biorefineries through the development of new knowledge, bio-technologies and products. The project comprises five key areas: pre-treatment and fractionation, hemicellulose, lignin and glycerol valorisation to higher value product streams. The project aims the demonstration of the technological and economic potential for integration and scale-up within biorefinery value chains.

The **MIRACLES** (FP7) project addresses the development of integrated biorefinery for valuable specialties from algae for application in food, aquafeeds and non-food products. Products will be developed for these markets and the technology used for algae production and biorefinery will be improved. New algae strains will be selected for extreme locations via bioprospecting to expand the resource base for algae cultivation. The project includes demonstrations to prove the techno-economic viability of the biorefinery concepts.

The project **BIOREF-INTEG** (FP7) was set to develop advanced biorefinery schemes to be integrated with existing fuel-production facilities in seven biomass-processing sectors (biofuels, conventional fuels, power, pulp and paper, the food and agricultural industries). The project identified reference cases and integrated biorefinery concepts for each biomass-processing sector and potential raw materials and promising added-value chemicals that could be produced. BIOREF-INTEG has provided critical insight regarding technical, economic and environmental considerations comparing reference and biorefinery cases.

The aim of the **D-FACTORY** (FP7) project was to set up a benchmark for a sustainable biorefinery using biomass Dunaliella salina microalgae tuning the alga to make naturally produced valuable compounds in different proportions. Dunaliella was be cultivated in open raceways and photobioreactors and then harvested using spiral plate and membrane technologies. A range of processing technologies were integrated and optimised using modelling techniques. A prototype D-FACTORY biorefinery was used to prove the business case for large-scale algae biorefineries.

VALOWASTE (FP7) dealt with the valorisation of waste streams from the agro food sector. The project developed a novel set of biochemical methods for the treatment of agrofood wastewaters. High-added value substances from the waste effluents could be recovered directly or could represent a substrate for biochemical processes to produce various bioproducts in biorefineries in addition to clean water and energy.

The aim of **SUSTOIL** (FP7) was to develop advanced biorefinery schemes to convert whole oil crops into energy (fuels, power and heat), food and bioproducts (chemicals and/or materials). Key objective was to improve the economics by valorising various by-products (rape meal, straw, glycerol) and to identify other ways for the use of oil-rich residues and by-products. SUSTOIL aimed to exploit the identified opportunities and investigate the potential of integrating these into existing vegetable oil / transesterification plants.

PROPANERGY (FP7) project was set to develop the technology for bioconversion of glycerine into value-added products and biogas at pilot plant scale. This allows complete use of glycerine and methanol residue from biodiesel production; the process will supply energy for product separation in the form of biogas and also yield two value-added products, to be used to produce polymers.

SYNPOL (FP7) aims to establish a platform that integrates the pyrolysis of various biowaste and biopolymer production with bacterial fermentation of syngas. The activities focus on the integration of innovative chemical, biochemical, downstream and synthetic technologies to produce a wide range of new biopolymers. It entails the implementation of novel microwave pyrolytic treatments together with systems-biology recombinant bacteria, that will produce biopolymer building-blocks to synthesize novel bio-based plastic prototypes by chemical and enzymatic catalysis.

SUBICAT (FP7) was set to address biomass conversion technologies by catalytic processes. The project identified a series of collaborative projects that would benefit from the mutual exchange of scientific expertise between academic and industrial partners. The network partners will establish links with world leading experts to develop optimal catalysts for ether cleavage in 'real life samples' of lignin for maximising the potential of lignocellulose as a source of fuels and fine chemicals.

AgriChemWhey (H2020) will build an industrial-scale biorefinery with integrated industrial and agricultural value chains to valorise over 25,000 tonnes dry matter of excess WP and DLP to several added value products. The Flagship plant will prove the techno-economic viability of the innovative WP/DLP-to-lactic acid technology and establish a new value chain for the production of high value sustainable food and feed products from other side streams. AgriChemWhey will also develop a blueprint of an economic sustainability concept and replication plans.

BioCatPolymers (H2020) will demonstrate a new route to convert low quality residual biomass to high added-value biopolymers, based on an integrated hybrid bio-thermochemical process. The goal is optimizing and demonstrating the entire value chain on 0.5 ton of biomass/day scale, including the pretreatment of lignocellulosic biomass, biological fermentation to MVL, separation of MVL, selective catalytic conversion to the targeted monomer and purification.

BIOFOREVER (H2020) will demonstrate 5 new lignocellulosic value chains and 3 valorisation routes for co-products utilizing 4 different cascading biorefinery concepts to establish optimal combinations of feedstock, biorefinery, end-products and markets to allow the implementation of these value chains in commercial scale. Chemicals, food and specialties will be produced.

The **BioMates** (H2020) project approach is based on innovative non-food/feed biomass conversion technologies, including ablative fast pyrolysis and mild catalytic hydrotreating, while incorporating renewable H_2-production technology as well as optimal energy integration. The proposed pathway for decarbonizing the transportation fuels will be demonstrated via TRL 5 units, allowing the development of an integrated, sustainability-driven business case encompassing commercial and social exploitation strategy.

BioRECO2VER (H2020) will demonstrate the technical feasibility of energy efficient and sustainable non-photosynthetic anaerobic and micro-aerobic biotechnological processes for the capture and conversion of CO_2 from industrial sources into 2 valuable platform chemicals, i.e. isobutene and lactate. The project will focus on minimizing gas pre-treatment costs, maximizing gas transfer in bioreactors, preventing product inhibition, minimizing product recovery costs, reducing footprint and improving scalability.

The **BIOSKOH** (H2020) project will make a two stage investment process and development path to realise the largest (110 Kton) 2G biorefinery in Europe. BIOSKOH realise the 1st stage Flagship plant to produce 55 kton of cellulosic ethanol per year. Biochemtex, Novozymes and Lesaffre developed, tested and demonstrated an innovative integrated pre-treatment, hydrolyses and fermentation package in the semi-industrial scale 2G biorefinery plant (Crescentino). This will be upscaled to the 1st of a kind commercial scale Flagship, to be built by Energochemica.

The **ENGICOIN** (H2020) project aims at the development of three new microbial factories (MFs), integrated in an organic waste AD platform, based on engineered strains exploiting CO_2 sources and solar radiation or H2 for the production of value-added chemicals (TRL 3 to TRL 5). This includes: produce lactic acid from biogas combustion flue gases or CO_2 from biogas purification; produce PHA bioplastics from biogas combustion flue gases and carbon from the AD; produce acetone from CO_2 from biogas purification.

EnzOx2 (H2020) plans to develop a 100% biochemical conversion of bio-based 5-hydroxy-methylfurfural (HMF) into diformylfuran, a platform chemical, and 2,5-furandicarboxylic acid (FDCA), a plastic building-block. Oxidases and peroxygenases will be used to perform the three-step oxidation of HMF to FDCA in a co-substrate and side-product free. Highly selective hydroxylation of plant lipids (fatty acids, terpenes and steroids) by peroxygenases will be optimized for cost-effective production of various chemicals.

The **Exilva** (H2020) flagship project will consist in the upscaling of the Borregaard's MFC process from the existing pilot plant (50-70 tons/year) to the full scale flagship plant (1000 tons/year) and the production of added value products in a sustainable way. The main tasks and challenges will be testing the equipment, technology transfer from the pilot to the flagship plant, gaining operational experience, establishing the plant organization and quality control, establishing the appropriate process parameters and gaining experience with regards to logistics and handling.

FALCON (H2020) aims to convert a lignin-rich industrial waste of 2G biofuel plants to higher value products, in particular shipping fuels, fuel additives and chemical building blocks. The lignin-rich waste is derived from sludge that is left after saccharification of the carbohydrates. The FALCON process is based on enzymatic and mild chemical conversion of the lignin waste stream. This implies an initial treatment at the 2G bioethanol plant, converting the waste to lignin oil. It will be further converted into fuel additives and chemical building blocks.

The **FUNGUSCHAIN** (H2020) project aims at the valorization of agricultural residues from mushroom farming to set up new cascading possibilities using innovative procedures to extract high value bio-based additives (antioxidants, antimicrobials, proteins), convert lipids into bioplasticizers and polysaccharides into biopolymers using remaining side streams to close the cycle by composting and/or biogas synthesis. Funguschain will demonstrate its industrial viability by building a new biorefinery revalorizing more than 65% of waste into valuable additives.

The **InDIRECT** (H2020) project will develop a biorefinery processes as part of new value chains to convert under-spent side streams/residues from the agro-sector and processing sector into marketable products. Cascading processes would increase the conversion efficiency and maximise the values of the feedstock. Activities from lab to pilot scale are foreseen, enabling the generation of sufficient material for application tests that are crucial for developing the downstream market.

InnProBio (H2020) aims to build a community of public procurement practitioners interested in Public Procurement of Innovation (PPI) with Bio-Based Products and Services (BBPS), supported by online network facilities. The project will develop a toolbox which will assist public procurers to inform themselves about BBPS and ultimately provide all relevant information to prepare an actual tender. The toolbox will be used for capacity building activities including trainings for public procurers and decision makers, market dialogues and exchanges with standardization experts.

IProPBio (H2020) targets to exchange complementary theoretical and experimental knowledge of research staff. The scope of activity will cover: design and integration of flexible and product-tailored processes; integration of chemical and biochemical routes into sustainable biorefining; relation between biomass extraction and separation processes and the properties of desired products; production processes integration into closed loop production.

LIGNINFIRST (H2020) targets a new approach based on an Early-stage Catalytic Conversion of Lignin (ECCL)-the Lignin-First approach, for the valorisation of lignin. ECCL involves the concurrent extraction and catalytic conversion of the lignin fragments in a one-pot process. LIGNINFIRST will address: (i) understanding the release of lignin fragments; (ii) advancing the understanding of H-transfer reactions, and; (iii) reaction engineering of the fractionation of biomass (catalytic upstream biorefining) to value-added products (catalytic downstream processing).

LIGNOFLAG project demonstrates an integrated and whole value chain oriented approach for ethanol production as fuel or chemical building block, based on Clariant's technology (e.g. onsite-enzyme production, tailor-made enzymes, chemical-free pre-treatment, intensive energy integration). The core part is the commercial flagship plant for lignocellulosic ethanol conversion (60,000 tons/year) that serves to showcase the techno-economic viability of an innovative bio-refinery concept.

MACRO CASCADE (H2020) will prove the concept of the cascading marine macroalgal biorefinery i.e. a production platform that covers the whole technological chain for processing cultivated macro-algae to highly processed value added products. The macro-algae biorefinery will be capable of processing multiple feedstocks, by using a range of mechanical, physico-chemical and enzymatic pre-processing and fractionation techniques combined with chemical, enzymatic or microbial conversion refinery techniques.

The **PEFerence** (H2020) project will establish an industrial scale (50 000 tonnes/year), cost-effective FDCA (diacid) biorefinery flagship plant producing bio-based chemicals and materials (bottles, films, Lego Bricks, polyurethanes). The consortium aims to replace fossil based polyesters (such as PET), and packaging materials with bio-based polyesters (such as PEF). The full value chain will be optimized ensuring cost-effective and environmentally sustainable production of FDCA, PEF/PBF and polyurethane products.

PULP2VALUE (H2020) developed multiple extraction techniques to isolate more valuable products from this large fraction of sugar beet pulp. The overall objective of this project is to further establish the value chains based on MCF, arabinose (Ara) and galacturonic acid (GalA). By demonstrating an integrated and cost-effective cascading biorefinery system to refine sugar beet pulp, PULP2VALUE aims to increase the value of the sugar beet pulp by demonstrating applications in high value markets.

RES URBIS (H2020) aims converting bio-waste into valuable bio-based products, in an integrated single biowaste biorefinery and by using one main technology chain. Targeted experimental activity focusses to solve a number of open technical issues (both process- and product-related), by using the appropriate combination of innovative and proven technologies. Territorial and economic analyses will be done either considering the ex-novo implementation of the biowaste biorefinery or its integration into existing wastewater treatment or AD plants for different production size.

The project **SSUCHY** (H2020) focusses on the development of bio-based composite constituents (i.e. biopolymers and plant fibre reinforcements) for the development of multifunctional biodegradable and/or recyclable bio-based composites. It is dedicated to the development of specific concepts, technologies and materials to achieve a complete value chain and prove the principle at the scale of product demonstrators.

The **STAR4BBI** (H2020) project will contribute at establishing a coherent, coordinated and favourable regulatory / standardization framework for the development of new value chains based on lignocellulosic feedstocks. The project focus will be on practical ways to modify regulations in such a way that alternative wording, product specifications, and/or measuring methods will eliminate hurdles without compromising the initial objectives of the standard or regulation.

SUN-to-LIQUID (H2020) project aims to establish a new path to synthesize renewable liquid hydrocarbon fuels from H_2O, CO_2 and solar energy. SUN-to-LIQUID aims at advancing the solar fuel technology from the laboratory to the next field phase. The complete integrated fuel production chain will be experimentally validated at a pre-commercial scale and with record high energy conversion efficiency. The ambition of SUN-to-LIQUID is to advance solar fuels and to guide the further scale-up towards a reliable basis for competitive industrial exploitation.

TASAB (H2020) is a novel algal biorefinery concept, offering an environmentally-sustainable closed system integrating thermal and biochemical conversion pathways. This concept would maximize energy production from algae for achieving a net positive energy balance and almost fully recycle nutrients to support algal large scale production and reduce the economic and environmental impacts of synthetic fertilizer use. TASAB will enhance and upgrade bio-oil yield and produce value-added products and biochemicals and would offset production costs for energy generation.

URBIOFIN (H2020) project aims to demonstrate the techno-economic and environmental viability of the conversion at semi-industrial scale (10 t/d) of the organic fraction of MSW (OFMSW) into: chemical building blocks (bioethanol, volatile fatty acids, biogas), biopolymers or additives. URBIOFIN will exploit the OFMSW as feedstock to produce different valuable marketable products for different markets: agriculture, cosmetics.

US4GREENCHEM (H2020) aims to design a biorefinery concept for the complete valorization of lignocellulosic biomass that is energy- and cost- efficient. The concept combines mechanical pre-treatment of the substrate with ultrasonic and enzyme treatment of lignocellulosic feedstock as substrate for sugar based biotechnological applications. This will help overcome its recalcitrance and disrupt inhibitors with mild CO_2 hemicellulose degradation and with the enzymatic recovery of sugars and technologies for the valorization of the by-products released in the process.

Zelcor (H2020) project aims at demonstrating the feasibility of transforming lignocellulose biorefinery recalcitrant side streams into high value biobased products, including fine chemicals. The concept combines chemical and enzymatic catalysis with biological conversion, within a biorefinery integrated approach. Zelcor is conceived to avoid waste production by recycling waste products and improve the sustainability of second generation biorefineries. It addresses three types of recalcitrant raw materials: lignocellulosic residues from ethanol production, lignins dissolved during pulping process and lignin-like humins formed by sugars conversion.

The **SYLFEED** (H2020) project consists in upscaling the bio-refinery process to a demo plant with a capacity up to 5 t/day of lignocellulose into ingle Cell Protein (SCP) to be used in aquaculture as animal feed, producing proteins for fish feed. SYLFEED will demonstrate the synergies between forestry industry and protein fish feed market, creating new high value opportunities for the former and an alternative, sustainable, protein source for the latter. The large challenge of the SYLFEED demonstration project is to upscale from pilot scale and validate the bio-refinery process that converts lignocellulose into SCP suitable to formulate fish feed.

The **4REFINERY** (SET-Plan flagship) project aims to develop and demonstrate the production of advanced biofuels that achieve overall carbon yields of >45%. 4REFINERY focuses on optimal pathways for advanced biofuels production through two primary conversion routes (catalytic fast pyrolysis and HTL) integrated with upgrading (hydro)refining processes. The goal will be to bring these technologies from TRL3-4 to TRL4-5. The project will establish relations between product and feedstock properties and relevant process parameters and allow a full understanding of the influence of feedstock and treatment processes on product characteristics.

The **Äänekoski bioproduct** mill in Finland (SET-Plan flagship project) is increasing the product portfolio with new bioproducts, generating bioenergy, while using no fossil fuels. In addition to pulp, it produces a range of bioproducts, such as tall oil, turpentine, bioelectricity, product gas, sulphuric acid and biogas. Upgrading of lignin and manufacture of textile fibres from pulp are at research stage. The mill produces 640 GWh district heat and steam and 1.8 TWh of electricity. The biogas plant will make use of the sludge from pulp production to produce 20 GWh of biogas a year.

MicroAlgae Biorefinery is a Climate-KIC project for an innovative and sustainable technology, for large-scale production of raw material for food and non-food purposes. Microalgae are among the most promising sustainable feedstocks because of the high productivity per hectare and the range of potential products. Innovation and industry collaboration efforts, however, are needed to develop microalgae biorefinery into a commercial activity for bulk-products.

The purpose of the **MET** project is to establish a fully integrated biorefinery in **Holstebro, Denmark,** funded by the NER300 programme. The plant is based on local biomass residuals and it will supply heat, electricity and transportation fuel. The plant will produce 64.4 Ml of ethanol, 77,000 t of lignin pellets, 1.51 Mm^3 of methane and 75,000 t of liquid waste annually which will be transformed into biogas and injected into the national gas grid. The process will use 250,000 t/year of straw. The operational phase will start in 2020. The total funding investment is EUR 39.3 million.

5 Technology development outlook

5.1 Technology trends and needs

The production of heat and power from biomass includes several technologies including biomass pre-treatment, anaerobic digestion, combustion, pyrolysis, hydrothermal processing, gasification and uses a wide range of biomass feedstocks (agricultural and forest waste and residues, industry residues and waste, food waste, energy crops. Bioenergy production is based mostly on a number of technologies that are well established (anaerobic digestion, combustion) while others are still in development at different stages (pyrolysis, hydrothermal processing, gasification). A number of technology combinations are possible and are under consideration that aims at improving the overall conversion efficiency of biomass, such as pyrolysis and gasification, or gasification and combustion of syngas in gas turbines, pyrolysis and gasification to produce clean syngas etc. A number of processes are currently under pre-commercial, demonstration, or earlier stage of development in a number of plants all over the world.

One major barrier for deployment of bioenergy technologies is the cost competitiveness in comparison to fossil alternatives, depending on the technology and process configuration (capital and operating costs, conversion efficiency, process reliability), plant capacity, feedstock (supply chain, type, quality, and cost), competitive uses (e.g. pulp and paper, wood processing industry etc.). Therefore significant R&D effort focussed on the improvement of the conversion efficiency, improving reliability, scale-up to benefit from the economies of scale, reduction of investment costs and improving the ability to use low-cost feedstock (agri and forest residues, municipal solid waste, sewage sludge, food waste, industrial waste etc.). Cost reduction depends on the maturity and advancement of technology. Also, difficult feedstocks require higher capital and operating costs, extensive effort for in gas cleaning, more expensive equipment etc. A number of technological trends have been observed in each conversion routes to address key constraints and needs for further improvement.

5.1.1 Biochemical processing

5.1.1.1 Anaerobic digestion

Anaerobic digestion is an established technology and to an extent demonstrated. The latest trends focussed to improve anaerobic digestion **performances**, **process control** and **optimise** the process, in order to increase the technical and economic viability of biogas plants. Process improvements could also result in a reduced need to clean the gas and removing contaminants that will improve processes integration with downstream processes. More R&D is needed on the development of technologies for measurement and control systems especially in co-digestion systems. An important R&D trend addressed the need to **enlarge the feedstock base**, to process new and difficult to degrade substrates, lignocellulosic feedstocks (agri-residues, straw, organic fraction of municipal solid waste sewage sludge). Future trends aims to develop new techniques to improve the biological **digestion** process (through hydrolysis pretreatment or enzymatic reactions, etc.), to increase the loading rate and advance dry fermentation and thermophilic processes need further development. There is the need to for the development of new techniques, enzymes to **improve biodegradability** and increase biogas yield and prove the viability of use of new substrates, such as micro and macro algae (freshwater and marine).

A significant trend in the R&D has been noticed to focus on **biogas upgrading** techniques to natural gas quality for biomethane production and injection into the natural gas grid or for the use as fuel in vehicle, as compressed biomethane. Many biogas upgrading plants are operating now using various technologies (Pressure Swing Adsorption, Pressurised Water Scrubbing, organic physical scrubbing, chemical scrubbing, membrane separation), benefitting from the various support schemes. More R&D would focus on the liquefied biomethane for the future use in heavy duty transport. R&D is also needed for reducing energy consumption both in the anaerobic digestion and the upgrading stage. Biogas upgrading to biomethane still requires technological improvements to **reduce energy intensity** and **improve cost performance** that could lead to reducing energy production costs. The methane slip from upgrading biogas to biomethane processes needs to be further investigated, as it can make a significant contribution towards the overall lifecycle greenhouse gas emissions.

5.1.2 Thermochemical processing

5.1.2.1 Biomass combustion

Biomass combustion technology is available for heat and power production and most bioenergy applications are based on biomass combustion. However, more R&D needs to focus mainly on developing **high efficiency** on combustion systems. The latest R&D trends focussed on achieving better understanding of combustion phenomena, application of computer simulation tools and numerical investigations to facilitate the analysis and design of **improved** combustion systems. R&D also needs to focus on the development and optimisation of **better boiler designs** and **advanced control systems** for improving efficiency and reduce the costs of energy generation.

R&D trends included the study of the **combustion behaviour** of various biomass feedstocks, including the use of low quality biomass, agri-biomass, investigating the **ash melting** behaviour to achieve a clear understanding of the complex chemistry and to identify mechanisms for deposit formation and the behaviour of aerosols from biomass.

There is also a need to develop boilers with increased **fuel flexibility** to be able to use a wide feedstock range (e.g. energy crops, agro-biomass, residues, waste recovered fuels, sewage sludge etc.). In order to reach **higher conversion efficiencies**, there is a need to develop **large scale advanced** systems with increased, supercritical steam parameters, above the state of the art steam turbine systems (500 – 525 °C). Higher temperature increases the high temperature corrosion risk, requiring R&D in **advanced materials,** reliable cleaning processes/technology, solutions to avoid deposit formation, and improved corrosion control processes that need to be demonstrated in long-term testing. There is the need to demonstrate the use of thermally treated biomass from different raw materials in large-scale heating and CHP applications.

There is a need for the development and demonstration of **micro and small scale** units to achieve improved reliability and high technical performances, and reduced costs. R&D focussed also on improvement of low emission small-scale biomass combustion, residential boilers, to achieve high efficiency and to reduce emissions. Biomass combustion in particular in small and medium-scale needs to further **reduce emissions** associated with small scale use of biomass, to meet increasingly stricter emission regulations, for the development of low emission stoves and boiler systems. There is a need to investigate flue gas cleaning systems and address catalyst deactivation issues.

An important issue is to make **better use of the heat** generated to improve the overall energy efficiency of the plants. R&D could lower the costs of heat networks, through optimum system design and reduced component costs. R&C should focus on system development for trigeneration/polygenertation, to develop cooling grid techniques/concepts, addresses plant design optimisation, the operation of a hybrid electric/heating/cooling grid with the integration of cooling systems and integration into cogeneration plants.

R&D trends aimed to demonstrate cost-effective and high efficiency energy generation systems using low and medium-temperature **waste heat** that are suitable for small scale systems to large scale systems. R&D could continue to develop advanced guidance and control systems, to achieve optimal integration of thermodynamic cycles in order to increase the electrical conversion efficiency. More R&D is needed to develop **hybrid systems** that combine biomass, biogas with hydrogen production, PV or concentrated solar systems, heat pumps, micro gas turbine and fuel cells. Further R&D is needed to integrate, optimize and demonstrate such systems at large scale.

5.1.2.2 Torrefaction

Torrefaction is a thermochemical upgrading process proved at pilot scale and a number of demonstration and commercial facilities are in operation. Further development of torrefaction is needed to overcome certain **technical and economic challenges**. The R&D focussed so far on the development of torrefaction and densification technology for a broad biomass feedstock range including clean woody biomass, forestry residues or agro-residues. R&D is needed on the development of **cost-effective** processes, product densification and scaling up the process. Further R&D is needed for finding the optimal configuration and **optimal process conditions** for producing a stable and high quality end-product, using a broad feedstock range. The optimal conditions needs to be tailored depending on several factors, such as the type of feedstock, product specifications (size, torrefaction degree), reactor technology and design, process control and heat integration.

Torrefaction process still needs to be demonstrated in **large-scale** applications using different raw materials and conversion technologies of different scales and torrefaction degree to prove the improved downstream process and cost efficiency. Future work should focus on **integrated torrefaction and densification** processes for the production of torrefied pellets and on integrated torrefaction and gasification for high-quality syngas production. Densification of torrefied biomass has improved over the last years due to a better understanding of the relation between biomass characteristics, torrefaction process conditions, and densification parameters.

Development of dedicated **analysis and testing methods** are needed for product properties. Product standards are under development to define fuel properties, e.g. degree of torrefaction, grindability, hydrophobic properties, etc. R&D work should focus on the assessment of **end-use** performance, for assessing the handling, storage, safety and milling behaviour and combustion **characteristics**, at full scale firing test trials. Ensuring consistent and controlled end product quality can create new markets and trade flows for biomass as commodity fuel and increase the feedstock basis.

5.1.2.3 Pyrolysis

R&D on pyrolysis focussed on generating process data for developing **pyrolysis process**, scaling up reactor, improving pyrolysis oil quality. R&D addressed one-step or two-step pyrolysis, catalytic and non-catalytic pyrolysis. R&D trends included investigations to improve the understanding of fast pyrolysis mechanisms, to determine the best operating conditions, and improve the process and design of pyrolysis reactors. R&D is needed on the pyrolysis conversion process, for improving process **reliability** and for broadening **feedstock** base for bio-oil. Further R&D is needed on improved pyrolysis reactor design, process optimisation to maximize bio oil yield and gas recycling for providing process energy needs.

Pyrolysis using various catalysts has been investigated to improve the **catalytic pyrolysis** by the use of novel catalysts, with reduced costs, optimization of catalyst selectivity towards desirable high value products. The most significant challenges for pyrolysis are related to quality of bio-oil, long-term stability, as well as the economics of its production and use. R&D addressed so far the improvement of bio-oil **quality**, bio-oil **cleaning** and **upgrading** to allow its use in downstream processes (heat, power, chemicals, synthetic fuels, and biocrude production). A key goal still remains the improvement of the **quality and consistency** of the pyrolysis oil in terms of stability, viscosity, moisture content, contaminants and corrosiveness.

In line with existing R&D trends, R&D should continue to address the improvement of bio-oil **quality and stability**, the control of bio-oil composition as well as on bio-oil upgrading, including hydrotreating, catalytic upgrading and fractionation. Bio-oil **upgrading** is challenging because of the high oxygen and water content of bio-oils. Improving the pyrolysis processes is an area of R&D to decrease pyrolysis oil water and oxygen content. R&D is needed for developing new techniques, including **catalytic pyrolysis** for upgrading, for the development and selecting the most promising catalyst. Catalyst improvement is a major opportunity in the upgrading step investigating catalyst deactivation, longer lifetime, better stability and cost. For the production of biochemicals from bio-oil or its fractions, the challenge is to assess and develop the most feasible isolation and **purification** methods. However, despite the progress made in fast pyrolysis and bio-oil production (TRL 4-5), the full integration of fast pyrolysis with upgrading is still required and many of the upgrading processes are still at TRL 3-4. Pyrolysis processes require **scale-up and demonstration** of bio-oil production technologies with different biomass feedstocks and mixtures.

5.1.2.4 Hydrothermal processing

In the hydrothermal processing, R&D focus has been addressing hydrothermal **carbonization**, **liquefaction** and **gasification** of a wide range of biomass streams and in particular to provide economically attractive and environmentally friendly alternatives to utilisation of wet biomass and produce bio-char, bio-oil (bio-crude), or gas (e.g., hydrogen, methane). Recent R&D focussed on **developing** hydrothermal liquefaction of diverse biomass feedstocks, increasing process integration and product recovery for the producion of bio-crude for multiple applications. The R&D trends include the understanding of relation between feedstock and process conditions, product yield and quality and the valorisation of residual process streams. Future R&D actions need to focus on expanding the **understanding** of hydrothermal liquefaction and the knowledge-base on reaction mechanisms and process kinetics of HTL. The greatest challenge yet to be addressed is to understand the impacts of **feedstock composition** and process conditions on **bio-crude quality**.

R&D needs include the development of continuous-flow liquefaction technology. R&D is needed to analyse the **effects** of feedstock, and the operating parameters, including temperature, pressure and the residence time on crude **oil yield and quality**. Future work has to involve testing various feedstock types to include tests to acquire critical process data and enable data analysis during biomass conversion into biocrude, tor establishing reactor configuration and process validation. R&D has to examine possible pathways to determine the **optimal operating parameters** for the development and demonstration of HTL process to validate current process assumptions, at large-scale, in long time operation. Better understanding of HTL process is needed to identify specific challenges and to develop **equipment** able to operate in extreme temperature and pressure conditions. There are research gaps with respect to **catalyst** performance, poisoning, loss, deactivation, regeneration and lifetimes. Improving the long-term use of catalysts is essential to improve their performance. Techno-economic analyses will have to be conducted as research and development progresses to identify and promote cost-effective conversion pathways.

5.1.2.5 Biomass gasification

Continuous R&D effort over the last years has led to significant progress, bringing biomass gasification to TRL 6-7. However, gasification needs significant **technological improvements** and requires demonstration at scale. R&D addressed the improvement of gasification process using a range of feedstocks. However, there is a need to investigate gasifier design, adjustment of operating conditions, in-bed catalysts/additives to achieve better syngas quality. Opportunities for improvement exist in the developing biomass pretreatment and gasification systems with greater feedstock tolerances. An alternative approach for more difficult feedstocks is to use pre-treatment technologies to improve the biomass quality such as the integration of fast pyrolysis processes before gasification.

R&D activities included the **optimisation and improvement** of biomass gasification process, as well as research on gas cleaning, upgrading, reforming process to obtain a clean syngas. Synthetic natural gas production via biomass gasification shows technical barriers including issues related to catalysts, affected by gas cleaning performances, achieving a stable syngas composition is still challenging. Key technical challenges and needs still include improving **process integration**, monitoring and control, gas clean-up and gas upgrading, improving performance and efficiency and reducing costs. R&D activities also aimed at studying, developing and testing the integration of biomass gasification and the syngas use in gas burners, gas engines, gas turbines or fuel cells.

There is still work to be done to prove continuous, **reliable long-term operation** of the different gasification systems at scale with a range of feedstocks.

Syngas cleaning and reforming is the biggest challenge in gasification due to the high content of impurities (particle, tar, alkali, chloride, ammonia, etc.), and the requirement for ultra-clean syngas for many downstream possible applications. R&D focus was on the development and demonstration of **syngas cleaning** technologies using both chemical and physical methods to the limits required for upgrading to syngas. There is a strong need for improved syngas clean-up and new **catalysts** for gas conversion, with greater resistance to poisoning, allowing syngas purification costs to be reduced. Despite previous efforts made in gas cleaning, tars remain a key problem, and **gas cleaning** to produce a gas that is ultra clean and that can be used in downstream processes, still remains a clear challenge for gasification. Further R&D is needed to optimise cleaning and conditioning, to develop integrated hot clean-up and reforming steps.

Several projects were set to **demonstrate** biomass gasification based on various concepts at full scale in several sites, with a capacity ranging from for small power to large scale. Technology development needs large scale demonstration of a fully integrated plant to address critical factors, such as the low reliability, sensitivity to feedstock quality, the variability of gas composition, slagging, corrosion and agglomeration.Key technical developments are still needed in order to improve the **technical and economical gasifier performances**, able to handle heterogeneous feedstocks, as well as to improve the efficiency of the production of high-quality syngas required by downstream processes.

5.1.3 Algae for bioenergy

Algae cultivation for bioenergy production requires a combination of **technical breakthroughs** on cultivation under different locations-specific conditions, but also on harvesting, dewatering, drying and conversion to the final product. R&D trends in the last years showed an interest toward gaining understanding of the **fundamentals** of algae and gain fundamental knowledge on algae metabolism, aerobic respiration, photosynthesis, and fermentation in organism. Much R&D needs to be done on species identification, the analysis of microalgae strains and selection of those with advantageous traits and/or genetic engineering to enhance the biomass productivity and yield of target components. R&D is needed on species characteristics to increase photosynthetic conversion efficiencies, to increase algae yields and energy content. A large challenge for microalgae is the contamination of open ponds and therefore there is need to o use/develop species that are resistant to a variety of conditions and less susceptible to contaminants/pathogens.

R&D aimed to develop, upgrade, and scale-up production of microalgae, to improve algae strains and **cultivation** techniques to reduce algal biomass production costs, using selected strains or improved microalgae species to make them better suited to specific growth conditions for different biochemical and biomaterials. R&D also focussed on the use of **carbon dioxide** from power plants and the **nutrients** from various waste streams, for the removal of micropollutants and nutrients (nitrogen, phosphorus, etc.) and for the improvement of the wastewater treatment process. While the majority of projects focussed on the use of microalgae, few projects addressed the cultivation and use of macroalgae.

There is a need for developing **large-scale cultivation** systems, including the development of cost-effective methodologies for off-shore and farms/land-based ponds cultivation, harvesting and conversion, improving yields, and proving economical production. Microlgae **harvesting** remains a critical challenge faced by algae cultivation. R&D is required on harvesting, separation and dewatering processes (e.g. centrifugation, flocculation, separation). Sea farming techniques and infrastructure would have to be developed for **macroalgae** cultivation, build on existing experience in macroalgae cultivation for food and additives for food, pharmaceutical, cosmetics and chemical industry. While some projects aimed to develop and demonstrate the biorefining processes of the algal biomass into high value products, ingredients and by-products, future R&D should focus on the demonstration at full scale of algae **processing**, including pre-treatment/hydrolysis processes (e.g. ultrasound and use of enzymes), oil extraction and biochemical (anaerobic digestion, fermentation) and thermochemical (pyrolysis, hydrothermal liquefaction) conversion technologies.

5.1.4 Biorefineries

Significant R&D effort targeted biorefineries that are largely at the conceptual stage, with new products, routes and process configurations being currently developed. R&D focussed so far on the development of bio-economy concepts, addressing a diversity of processes, feedstocks and intermediate carriers and final products, using various biochemical and thermochemical pathways. R&D focussed on advancing theoretical and experimental knowledge on reaction mechanisms, process engineering and processes integration. R&D focussed to develop biorefinery concepts using organic **waste streams** to produce various compounds, chemical building blocks, biopolymers or additives, and value-added fine chemicals. Integrated algae biorefineries were investigated, incorporating a range of processing technologies for the production of a range of added-value products from **microalgae** and **macroalgae**.

One of the challenges for the deployment of biorefineries relates to the **technical maturity** of a range of processes to produce bio-materials, bio-chemicals and energy as well an on their integration. The most important challenge is the lack of **large scale demonstration** of these technologies. Further R&D is also needed for the development and **integrating** new **biochemical and thermochemical** conversion processes, the adaptation and optimisation of downstream processing. An important issue refers to the improvement of process stability and ensuring end-product quality. A key point is the integration and adaptation of biochemical processes to up-stream processes that can result in by-products that inhibit down-stream processes. Thus biorefineries requires R&D along the entire biorefinery value chain, **optimising** various processes, to maximize product and energy yield and efficient use of biomass, energy, water and nutrients. Modelling tools and methods are needed to estimate the technical and economic **feasibility** of biorefinery concepts. Further R&D should focus on scale-up activities from pilot scale to demonstration scale and to prove viability in commercial operation.

5.2 Technology projections

The technology projections, based on the JRC-EU-TIMES model (Simoes et al., 2013), has been used for analysing the role of the biomass up to 2050 in the EU energy system for meeting the EU's energy and climate change related policy objectives. The JRC-EU-TIMES depicts possible deployment rates for heat and power from biomass technologies up to 2050, as part of the complex European energy supply system, among the other conventional and renewable energy technologies, under different scenarios. This takes into account the sustainable bioenergy potential in Europe and the competitive use of biomass for heating, electricity and biofuels production in different scenarios.

The JRC-EU-TIMES is a partial equilibrium energy system model maintained by the Institute for Energy and Transport (IET) of the Joint Research Centre (JRC). It aims to analyse the role of energy technologies development and their potential contribution to decarbonisation pathways of the energy system. The model is a linear optimisation, bottom-up technology rich model, providing as a result the annual stock and activity of energy supply and demand technology at EU and Member States level in different scenarios. It models technologies uptake and deployment and their interaction with the energy infrastructure in an energy systems perspective.

The JRC-EU-TIMES model results show the trade-offs for technology deployment, under different scenarios, i.e. under different assumptions and input data. For heat and power from biomass, investment cost (CAPEX, levelised cost of electricity (LCOE)) and efficiencies data. The results highlight the relevance of different factors for a specific technology deployment, including technology advancement and the limitations of biomass potential. Such factors are energy policy goals, sustainability constraints, subsidies to technologies, investments in R&D, research breakthroughs, higher/lower cost for energy technologies. The model provides data on the expected installed capacity (GW), the electricity production from biomass, the contribution of biomass resources to bioenergy, the share of biomass uses in different sectors and the primary energy consumption, until 2050.

Climate and policy scenarios

The JRC-EU-TIMES model 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.** The "Baseline" scenario is used to cover the lower end of global RES deployment. The global deployment of RES is based on the "6DS" scenario of the Energy Technology Perspectives published by the IEA in 2016. It represents a world in which no additional efforts are taken on stabilising the atmospheric concentration of GHGs. In the EU, it is assumed that there is a 46% CO_2 reduction by 2050;
- **Diversified.** The "Diversified" portfolio scenario is taken from the "B2DS" scenario of the IEA's 2017 Energy Technology Perspectives and is used as representative for the mid-range deployment of RES. All known supply, efficiency and mitigation options are available and pushed to their practical limits. Fossil fuels and nuclear energy participate in the technology mix, and CCS is a key option. In the EU, the 2050 CO_2 reduction target of 80% is achieved.
- **Pro-RES**: this scenario is the most ambitious in terms of capacity additions of RES technologies. In this scenario, the world moves towards decarbonisation by significantly reducing fossil fuel use; however, in parallel with a strong decrease of nuclear power. CCS is not an available mitigation option. The deployment of RES is based on the 2015 "Energy Revolution" scenario of Greenpeace. In the EU, the 2050 CO_2 reduction target of 80% is achieved.

The scenarios were further divided in sensitivity cases by considering different technologies, resources and policies strategies, as illustrated in Figure 6 and **Error! Reference source not found.**.

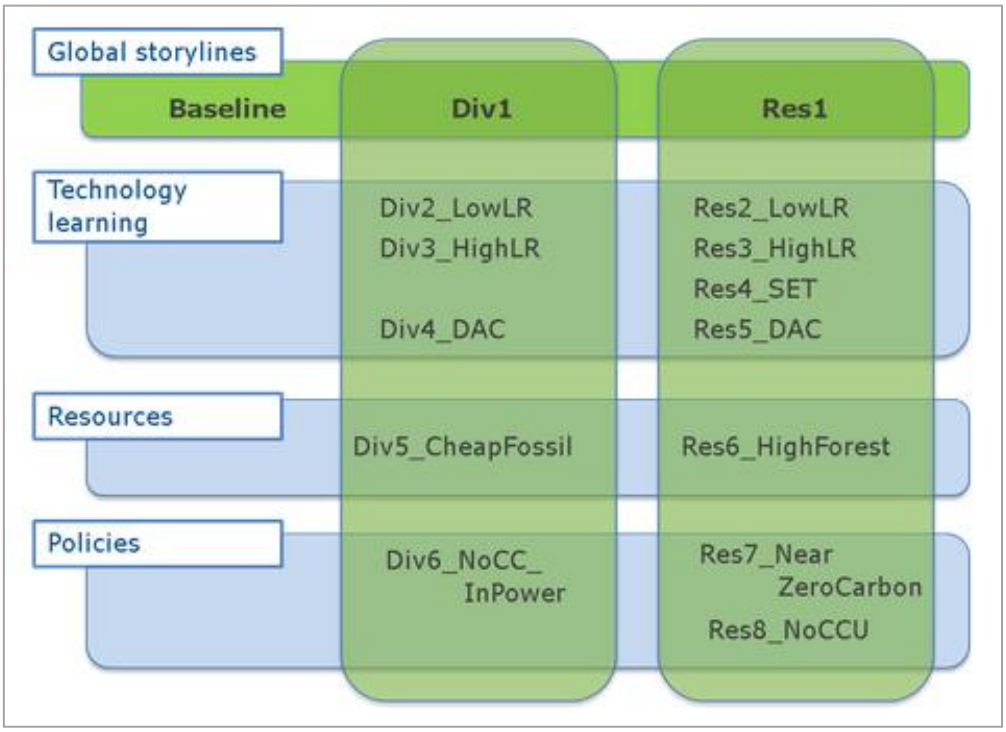


Figure 6. Global Storylines that covers worldwide development of low carbon energy technologies to 2050. (Source: JRC EU TIMES)

Deployment trends

Biomass conversion technologies are modelled explicitly in the JRC-EU-TIMES model including current technologies, from combustion (small/large heating and small/large CHP) to AD (small/large biogas, waste digestion, biomethane) or gasification. The techno-economic parameters associated with each technological option are included in the model separately (JRC EU TIMES).

The simulations show that the installed capacity of biomass power have an upward trend in all considered scenarios for 2050 (Figure 7 and Figure 8). The modelling results indicate that the installed capacity will increase steadily until 2030, when the trends begin to differ among them. In fact, it is possible to observe three major trends, as follows:

- Diversified scenario: rapidly increase of the installed capacity until 2030, when it reaches the amount of 72 GW. From this point, there is a marginal variation of the results, reaching 75 GW in 2050;
- Baseline and Pro-RES scenarios: both scenarios show a decreasing trend after 2030, when they will have capacities around 73 and 69 GW, respectively. The Pro-RES scenario has a higher decrease in a long term, reaching 57 GW in 2050, in comparison to 67 GW for the Baseline scenario for the same period. The Pro-RES is the only scenario that will have inferior installed capacity of bioenergy plants compared to the Baseline scenario; and
- Pro-RES with Near Zero CO_2 and with No-CCU scenarios: in these scenarios, the installed capacity changes slightly in the period of 2030-2040, but increase rapidly in the last simulation period. In 2050, the capacity will reach 105 and 96 GW, respectively.

Table 9. Parameters considered in the JRC-EU-TIMES modelling scenarios.

Name	Learning	CO_2 2050	NUC +20yr	New NUC	CO_2 STOR	CO_2 Reuse
Baseline	REF	-46%	YES	YES	YES	YES
Diversified	REF	-80%	YES	YES	YES	YES
Diversified: Low LR	LOW	-80%	YES	YES	YES	YES
Diversified: High LR	HIGH	-80%	YES	YES	YES	YES
Diversified: DAC	REF	-80%	YES	YES	YES	YES
Diversified: Cheap Fossil	REF	-80%	YES	YES	YES	YES
Diversified: NoCC InPower	REF	-80%	YES	YES	YES	YES
Pro-RES	REF	-80%	YES	NO	NO	YES
Pro-RES: Low LR	LOW	-80%	YES	NO	NO	YES
Pro-RES: High LR	HIGH	-80%	YES	NO	NO	YES
Pro-RES: SET	SET	-80%	YES	NO	NO	YES
Pro-RES: DAC	REF	-80%	YES	NO	NO	YES
Pro-RES: High Forest	REF	-80%	YES	NO	NO	YES
Pro-RES: Near Zero CO2	REF	-95%	YES	NO	NO	YES
Pro-RES: No CCU	REF	-80%	YES	NO	NO	NO

Source: JRC EU TIMES

Considering only biogas plants, the results suggest that the installed capacity will growth until 2030, reaching values around 82 GW in the aforementioned scenarios. After this period, most of the scenarios indicate a decrease in their capacities, except the Pro-RES with No-CCU scenario, which shows an opposite trend. In 2050, the total installed capacity of biogas plants will reach values between 24 and 95 GW, depending on the analysed scenario.

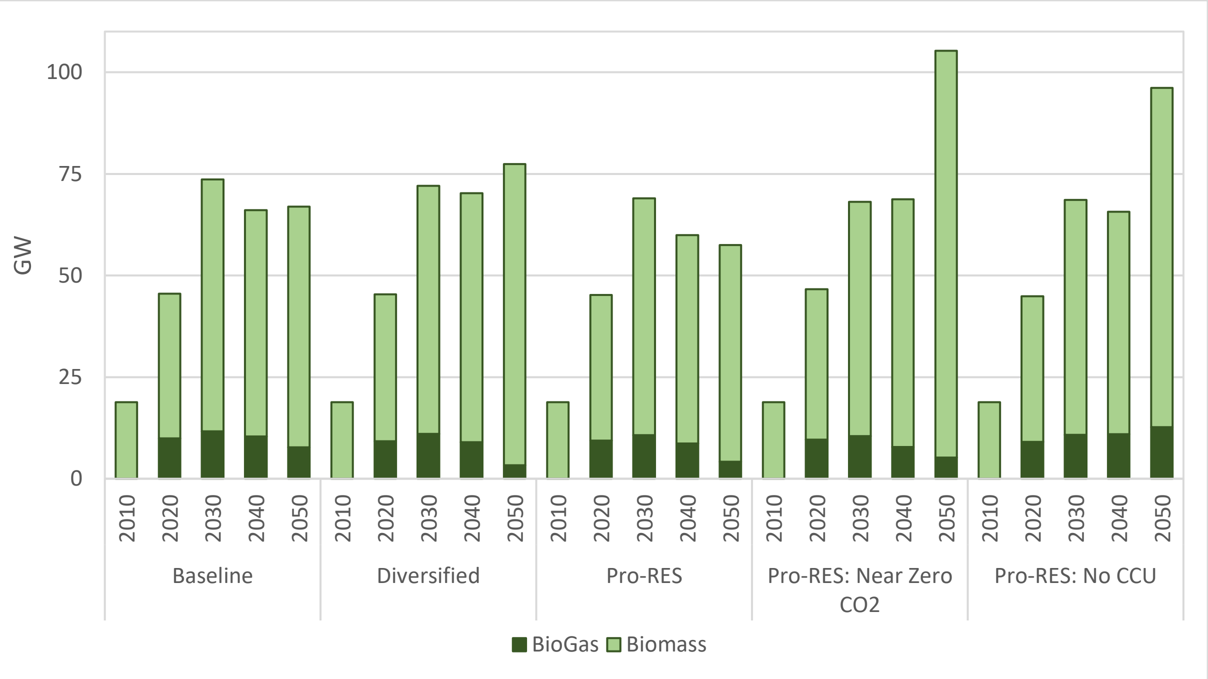


Figure 7. Evolution of the installed capacity by bioenergy resources based on JRC-EU-TIMES simulations [GW].

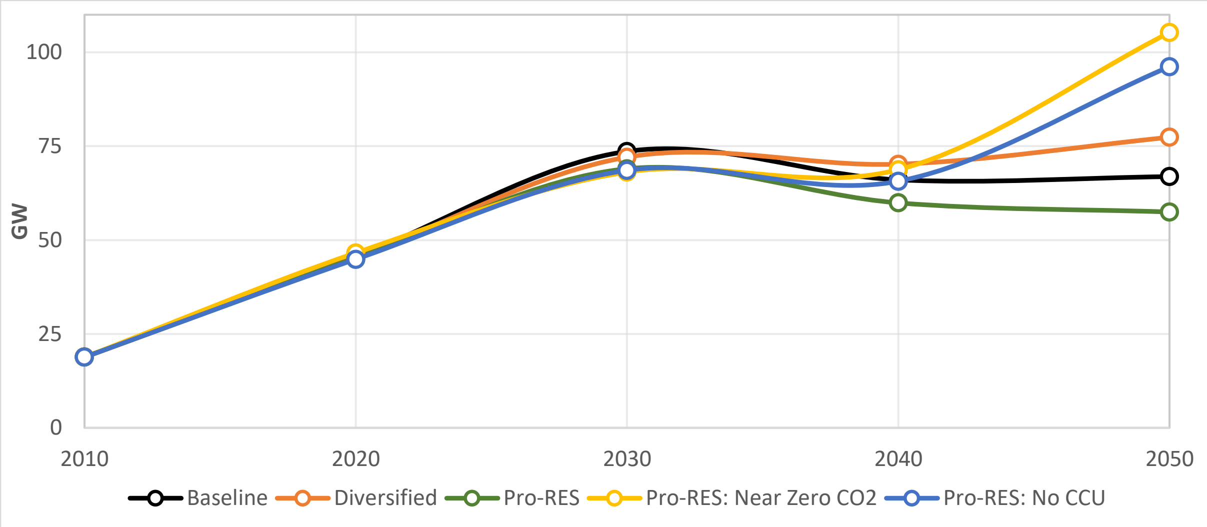


Figure 8. Evolution of the total installed capacity of bioenergy plants based on JRC-EU-TIMES simulations [GW].

The analysis of the electricity production from bioenergy plants shows similar trends from the installed capacity simulations (Figure 9 and Figure 10). The different scenarios will keep the growth trends until 2030, when they will reach production values between 240 and 260 TWh. The period of 2030-2040 will not see significate changes of the trends, except for the Pro-RES scenario that will have an inversion of the trend (decrease of the production), reaching 185 TWh in 2050. The other scenarios show increase trends in the last simulation period, especially for the Pro-RES Near Zero CO_2 and Pro-RES No-CCU scenarios, which will reach production values of 367 and 324 TWh, respectively.

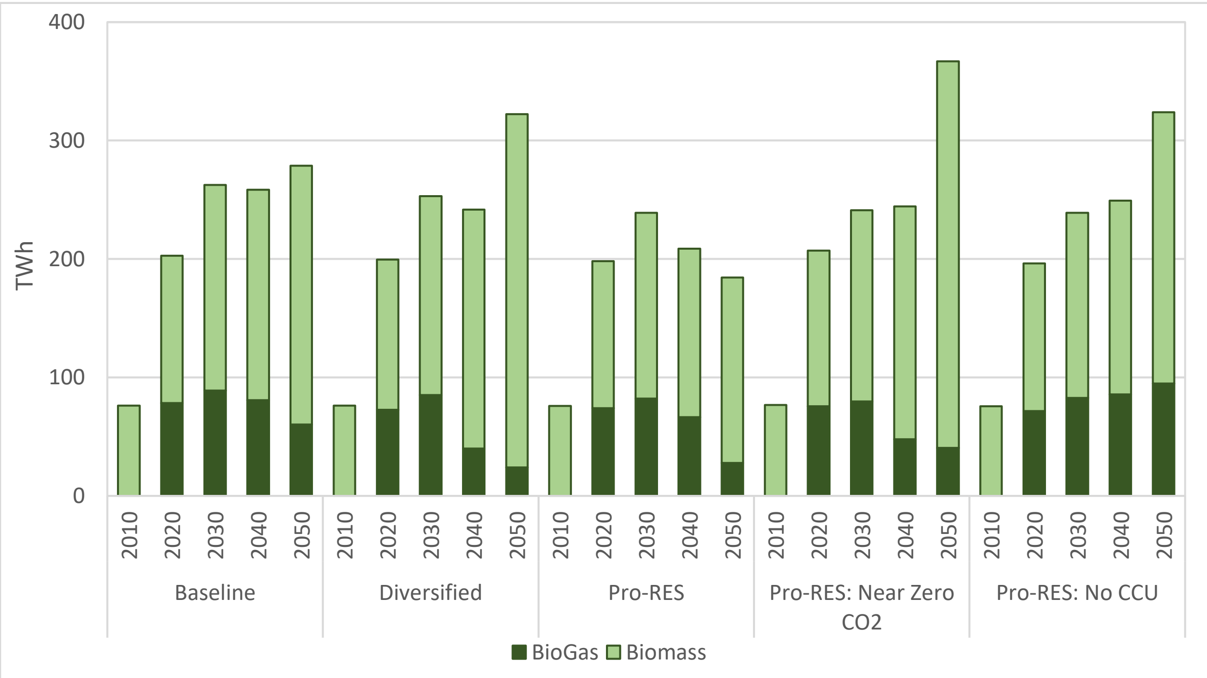


Figure 9. Evolution of electricity production by bioenergy resources based on JRC-EU-TIMES simulations [TWh].

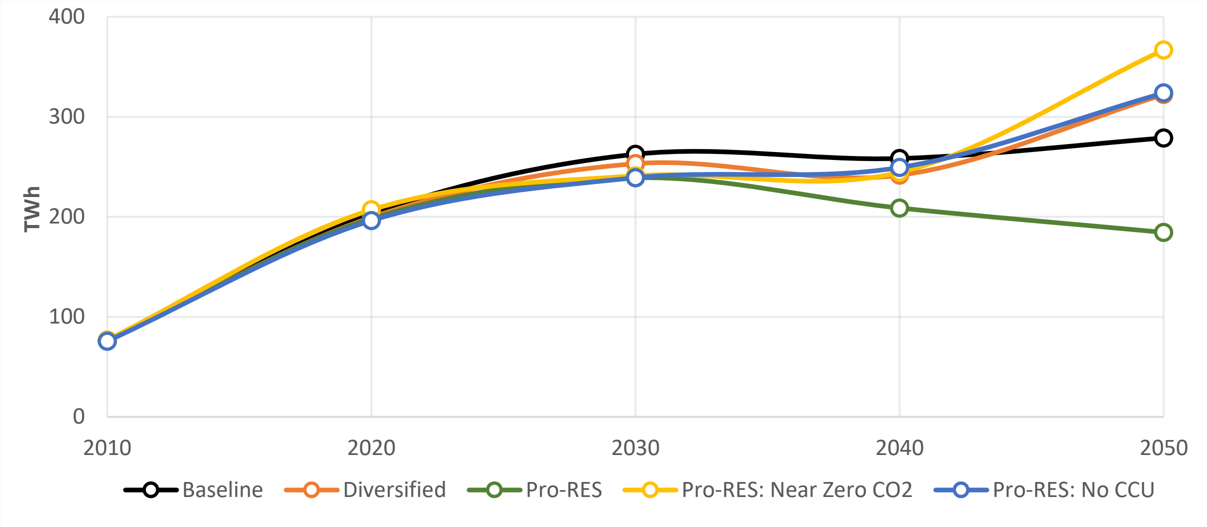


Figure 10. Evolution of the total of electivity production of bioenergy plants based on JRC-EU-TIMES simulations [TWh].

The JRC-EU-Times model projections show that the use of biomass for power production will increase until 2050 (Figure 11 and Figure 12). The Pro-RES Near Zero CO_2, the Pro-RES No-CCU and the Pro-RES scenarios estimate the production of 7000 PJ of primary energy in 2050, while the Baseline and Diversified scenarios suggests the production of 6000 PJ in the same period. In these scenarios, most of the biomass resources will come from forest and agro systems, followed by bioresidues / biogas resources, and energy crops.

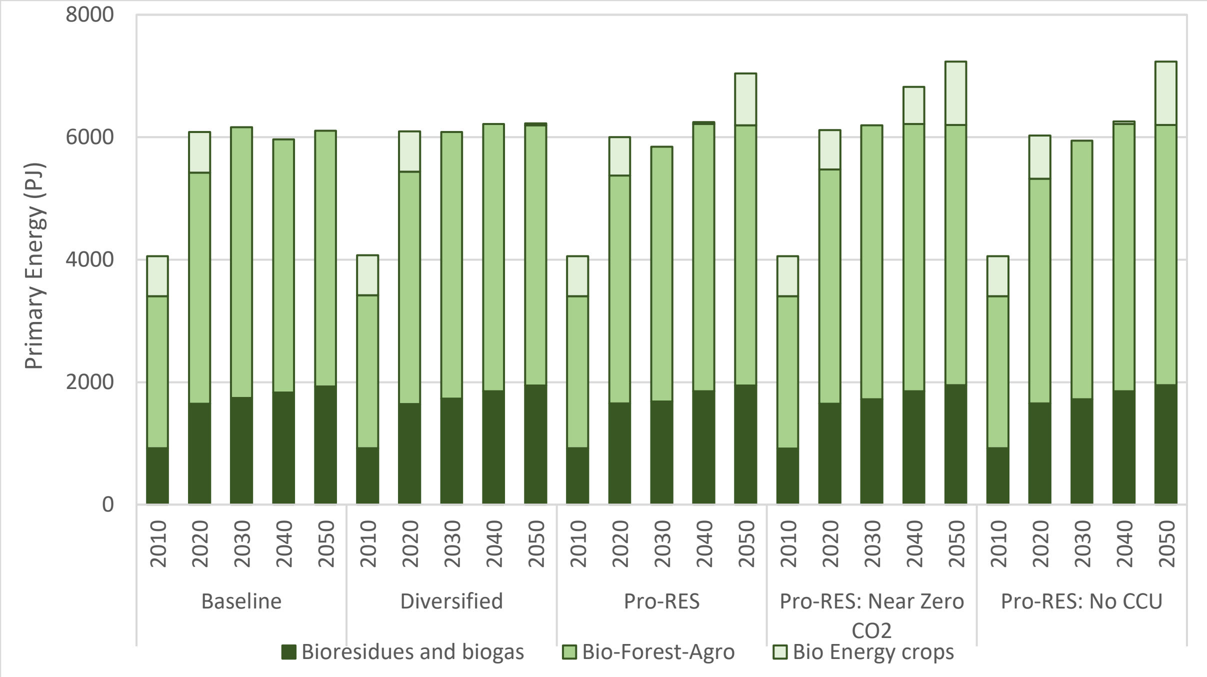


Figure 11. Evolution of the primary energy production by bioenergy resources based on JRC-EU-TIMES simulations [PJ].

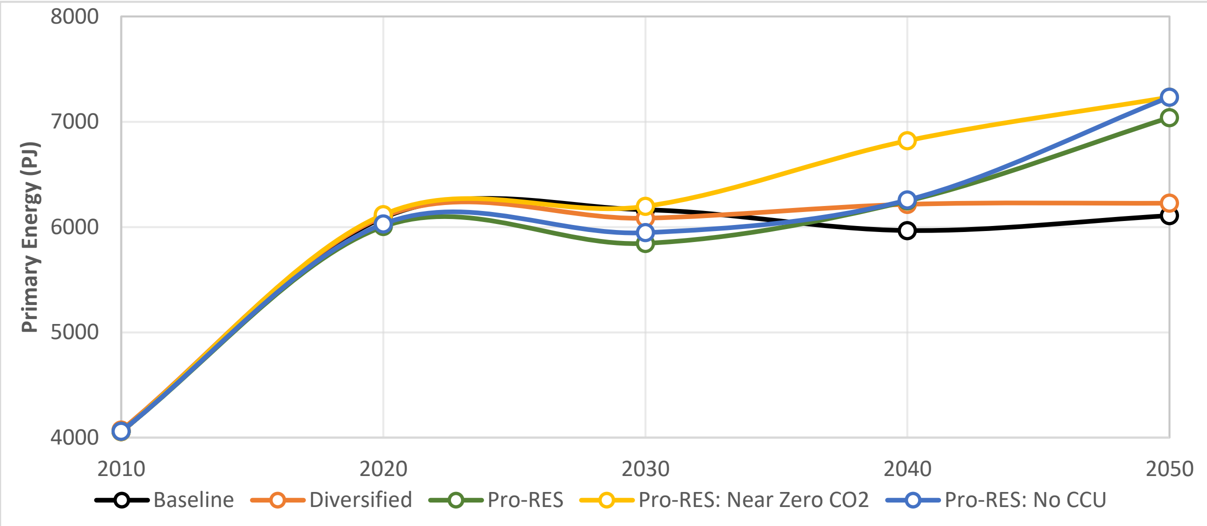


Figure 12. Evolution of the total of primary energy production of bioenergy resources based on JRC-EU-TIMES simulations [PJ].

5.3 Technical barriers to large scale deployment

5.3.1 Biochemical processing

5.3.1.1 Anaerobic digestion

Anaerobic digestion is a well-established technology and to an extent demonstrated. One of the main barriers for biogas production through AD is the economic viability, which is highly sensitive to feedstock price, process configuration and plant size. Biogas projects need high investment, operation and maintenance costs, especially for smaller scale. The scaled-down of AD plants still needs to be achieved, in order to better valorisation of small waste streams. The costs of biogas production are highly depending on the substrate used. While higher capacity plants are more economic, their capacity is limited by the availability of sustainable feedstock. Easily digestible substrates (such as energy crops) are more expensive, but require less investment costs having higher biogas yield, which results in smaller biogas reactors. Difficult substrates (such as agri-residues) on the other hand, are cheap (often with a negative price) but require large investment costs and more complex pre-treatment processes involved.

The improvement of technical and economic viability of biogas plants still require technology development, better control and process optimisation, improved biological digestion process through hydrolysis treatment or enzymatic reactions, or the use of new bacterial strains with a greater tolerance to process changes and feedstock type. New processes such as dry AD and thermophilic digestion that would allow the use of difficult substrates and faster degradation are not yet mature and need to achieve technological improvements. An additional barrier for biogas deployment is the need to clean, purify and upgrade biogas to biomethane through extensive processes for the treatment and removal of contaminants in order to be used in multiple applications. So far the subsidies for biomethane production in the form of investment grants and/or feed-in tariffs have contributed to the advancement in the upgrading technology, which still needs to be proven in commercial operation. Therefore, biogas upgrading to biomethane requires technological improvements to reduce energy intensity and improve cost performance of biomethane. An additional barrier to economic viability of biogas production relates to the possibility to use the heat produced in CHP systems.

5.3.2 Thermochemical processing

5.3.2.1 Biomass Combustion

A key barrier for the large scale deployment of biomass combustion is the low competitiveness of bioenergy in comparison to fossil fuels. Bioenergy technologies require significant investment in additional equipment needed for handling, pre-treatment and feeding and for gas cleaning, as well as increased maintenance and repair costs. However, where cheap or no-cost biomass feedstock (residues from agriculture and forestry waste) is available, biomass combustion is an economically viable option for energy production.

Scale effect is particularly important for biomass plants, with specific investment costs increasing significantly with the decrease in the plant capacity - the lower the plant capacity, the higher the specific investment costs are. Increasing the scale is thus an option for increasing the plant efficiency, but additional issues need to be considered, such as the availability of low-cost biomass feedstock, and logistics of feedstock supply. In addition, increasing the demand of biomass increases the area of collection and thus the biomass cost associated with the transport cost, need to be considered.

From the technical and operating point of view of a bioenergy plant, reduced conversion efficiency (25 - 35 % in biomass plants in comparison to conversion efficiency that ranges between 35 – 44 % for oil, gas or coal power plants) are important barriers for biomass combustion. One of the main options to increase the efficiency of power generation and the competitiveness of bioenergy has been the switch from separate power production and heating plants to CHP production. CHP is typically the most profitable choice for power production with biomass if heat could be used for industrial use or heating in building such as district heating. Yearly variation in heat demand for heating in buildings is however an important factor to consider.

Higher conversion efficiencies could be achieved by increasing steam parameters above the state of the art steam turbine systems (500 – 525 °C) to supercritical steam, the addition of a steam reheater and optimisation of the overall plant design. Increasing the power-to-heat ratio in CHP plants can be another option to achieve higher-efficiency depending on the regional heat demand. Higher temperature increases the high temperature corrosion risk, requiring advanced materials, reliable cleaning processes/technology, solutions to avoid deposit formation, and improved corrosion control processes that need to be demonstrated in long-term testing.

The variability of physical and chemical properties of biomass feedstock poses significant challenges for the operation of the biomass plants. The problems associated with slagging, fouling and corrosion related to the physical and chemical properties of biomass (such as high alkali content) are still significant in biomass plants, in particular for some agri-residues. Biomass combustion requires on-line monitoring techniques, for example for fouling, corrosion and agglomeration. Biomass combustion, in particular in small and medium scales, needs to further reduce harmful emissions in order to meet increasingly stricter emission regulations. It can be achieved by the development of low emission stoves and boiler systems using extreme stage combustion and improved design and filters, but they are quite expensive.

5.3.2.2 Torrefaction

During the last years, the biomass torrefaction technology has improved significantly. Torrefied biomass is able to address some challenges related to biomass supply chains, especially with regard to transport, handling and storage, and logistic cost. The torrefaction technology has been proven at pilot scale and a number of demonstration and (semi)commercial facilities are in operation (Cremers et al 2015). Further development of torrefaction technology is needed to overcome certain technical and economic challenges. Depending on the reactor type, it can be a serious challenge to scale up a torrefaction processes from pilot to commercial scale. Using multiple modular torrefaction might be an approach for upscaling.

The most important technical challenges in the development of torrefaction processes relate to achieving constant and controlled product quality. The consistency of the product is a challenge, since the torrefaction process involves many parameters, including wide-ranging biomass quality, particle size and operating parameters, such as reactor temperature, residence time, or heat transfer rate. Many fuel properties (e.g. degree of torrefaction, grindability, hydrophobic nature, resistance against biodegradation) have not been thoroughly defined or standardized. Finding the optimal process conditions for producing a stable and high quality end-product is still needed. The control of the temperature profile and residence time of the solid biomass during the torrefaction process is crucial for an efficient process and optimal product quality (Cremers et al 2015). There is limited knowledge on process performance, properties of torrefied product and composition of volatiles. Additional technical challenges relate to the torrefaction gases, which consist of CO_2, CO and various gaseous organic compound, including particulates and heavy tars that might result in operational problems. Torrefied biomass is more difficult to press into pellets than raw biomass depending on biomass type, moisture content, particle size, type of mill and pellet size that requires optimization of the process conditions during torrefaction as well as pelletisation.

5.3.2.3 Pyrolysis

Bio-oil production through fast pyrolysis represents an attractive route to bioenergy production. However, it is still at an early stage of development and needs to overcome a number of technical and economic barriers to compete with traditional fossil fuel based techniques. Pyrolysis produces solid, liquid and gaseous fractions. Maximising bio-oil yield is necessary to achieve cost effectiveness of pyrolysis process. Research is needed to achieve better understanding of the conversion process. The influence of feedstock properties, feedstock ash, heat transfer rate, reaction time, temperature profile, and/or the addition of catalysts on the liquid fraction yields still needs to be better clarified. The development of commercial scale, efficient and stable catalysts for pyrolysis is additional challenge. The potential of bio-production and upgrading has not been validated at large scale and more efforts are still needed. The improvement of cost-effectiveness of the process is a key issue. There is need to characterize and develop standards for the use of bio-oil and develop and test a wider range of energy applications.

Although bio-oil is a promising alternate to fuel oil, its direct application without chemical upgrading is limited due to its characteristics, requiring further upgrading for most applications. Key technical challenges of pyrolysis technology include the characteristics of the pyrolysis oil (such as the high oxygen content), long-term stability, as well as the economics of its production and use. A key goal is thus the improvement of the quality and consistency of the pyrolysis oil in terms of stability, viscosity, oxygen content, contaminants and corrosiveness (IEA 2009, IRENA 2016). Better understanding is needed on the effect of biomass feedstock characteristics and process parameters on the quality and subsequent use of the bio-oil, to identify best ways to overcome the problems related to thermal stability and process reliability. Bio-oil upgrading is challenging because of the high oxygen and water content of bio-oils, although several options are available. A significant technical barrier relates to bio-oil production and the integration of bio-oil production and upgrading steps.

5.3.2.4 Hydrothermal processing

Hydrothermal processing is under development at lab-pilot scale to pilot-industrial scale, with some projects closer to demonstration. While several projects have shown favourable results in terms of carbon and energy recovery efficiencies, there are still a number of technological challenges that need to be addressed. Technological gaps include reactor design, various plant components and the selection of adequate materials to avoid corrosion in the extreme environment in the process. The requirements of high temperature and pressure involve the need for advanced equipment used in the process, such as pumps for high concentration slurry operating at these conditions. A breakthrough is needed in the research and development of new materials. Investigations on the continuous flow system are needed to understand process development for commercial applications (Kumar at al 2018, IRENA 2016).

There is a wide range of potential process designs, and the optimal process parameters and other important influencing factors need to be established in order to achieve high conversion efficiency. The nature and yield of products from hydrothermal processing should be further investigated to reveal the effect of factors such as biomass composition, process conditions, nature of the solvent, reaction temperature, retention time, and catalyst. Fundamental and applied research is needed, building knowledge of process kinetics, reaction rates, products formation and decomposition from biomass hydrothermal processing. This knowledge will contribute to understand how to optimize reactor design. Considerable effort is needed to comprehend bio-oil stability and quality and thereby better understand ongoing process reactions and subsequent upgrading requirements. Detailed characterization of all the products and intermediates is needed (Kumar et al 2018). Longer-term testing and detailed characterization of catalyst performance, stability, regeneration, and lifetime are needed, considering the important role of catalyst in determining process yield and performance. HTL oil and aqueous phase separation needs further work to understand the conversion of organics in the aqueous phase and to recover the organic material into the oil phase.

The integration of hydrothermal liquefaction process with subsequent bio-oil upgrading and conversion technologies should be an important research direction in order to reduce the cost of the integrated processes. There is a need to understand the toxicity of trace compounds and the impact of organic compounds on wastewater treatment. Along with technological constraints, there are economic bottlenecks. As the technology uses high pressure equipment, the process has high capital investments (Cao et al 2017, Kumar et al 2018). The key points for developing the HTL of biomass are to reduce the operating costs and optimize the reaction conditions to improve the yield and quality of bio-oil.

5.3.2.5 Biomass gasification

Biomass gasification after years of development requires demonstration at scale and needs significant technological improvements. The technological challenges are complex, since syngas needs to be clean and to comply with the technical requirements of downstream processes. Advanced gasification applications require significant **upscaling** and needs to prove to be economically competitive in comparison to other fossil fuels energy production options. An important aspect of gasification applications is the high initial investment costs, especially of the first plants, in addition to the high financial risks involved. Because of the technical faults, especially regarding gas cleaning and ash-related problems, many of the large scale gasification plants have been abandoned. Technical advances in the conversion efficiency of biomass into syngas, syngas conditioning and upgrading may improve the overall process performance and contribute to reduce both the capital and operating costs.

There are a number of key technological challenges that regard the commercial application of biomass gasification for power generation. Low operational availability of gasifiers and gasification-based technologies is one of the barriers to commercial deployment gasification plants and syngas production. Work is still needed to demonstrate reliable, long-term operation at scale of the different gasification systems, using a variety of feedstock input while providing the syngas requirements necessary for downstream applications. The optimisation of gasifier operating conditions and specific syngas compositions, as well as the efficient thermal integration of the various steps of biomass pre-treatment, gasification, syngas clean-up and upgrade have been identified as major challenges. Gasifier reactor and process optimization would lead to increasing gasifier availability and efficiency, improving performance, and reducing the capital and operating costs of gasification. Achieving a stable syngas composition is also challenging. The gas composition and level of contaminants vary depending on the biomass feedstock, gasifier design, gasifying agents, and gasification conditions. Biomass properties significantly affect the operation of the gasifier, product gas composition and overall efficiency. The short lifetime of the catalysts is the main specific technical barrier for the synthetic natural gas production.

Technological hurdles for biomass gasification mainly include gas cleaning and tar reduction, because most **downstream processes** require a **high-quality syngas**. Therefore, the raw syngas must be cleaned to remove dust, alkali metals, halogens, sulphur, tars or even CO_2. Tars remain a key problem, and several high temperature tar cleaning options are under development. 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. Syngas processing needs to be efficiently integrated into the plant, optimized with the temperature and pressure requirements of downstream systems, and to meet syngas product specifications. Some gas cleaning processes (specifically low temperature processes such as water scrubbing) produce significant volumes of contaminated wastewater that needs to be cleaned (IRENA 2016).

5.3.3 Algae

There are significant barriers for commercial production of algae for energy that range from incomplete knowledge of algae biology to the challenges associated with large-scale integration of algae production. One important prerequisite to grow algae commercially for energy production is the need for large-scale systems so that economy of scale could reduce production costs. Given the large number of algae with different characteristics it is not yet clear which algae species would be best suited for specific bioenergy applications. The identification and development of energy efficient and cost-effective biofuels pathways based on algae is a challenge, given the large variety of algal strains, their growth conditions, yields and chemical compositions. Algae systems have to be optimized for a particular bioenergy pathway, integrating cultivation, harvesting and conversion into the final product for improved energy output and economic performance.

Algae cultivation for bioenergy production requires a combination of technical breakthroughs on cultivation under different specific conditions, but also on harvesting, dewatering, drying and conversion to the final product. In particular, considering the microscopic size and properties of microalgae strains, the development of harvesting and dewatering technologies represents a major challenge and a critical issue with respect to energy requirements and costs. Capital intensity of algae production is high and thus it is essential to reduce the capital cost of several components to a few main components. Algae-based bioenergy production is not foreseen to be economically viable in the near to medium term. The relatively high cost of producing algal biomass remains the most critical barrier to commercial viability of algae-based production (Laurens et al. 2017).

There is a need for developing large-scale cultivation systems, including the development of cost-effective methodologies for off-shore and farms/land-based ponds cultivation, harvesting and conversion, improving yields, and proving economical production. A large challenge for algae is the difficulty of maintaining selected species in outdoor culture, since open cultivation systems for micro-algae are susceptible to contamination from external sources, with severe impact on algae productivity. One of the major barriers to large-scale cultivation of algae includes high demands of water and nutrients for algal growth. Water use requirements for algal biomass and biofuel production vary depending on growth conditions, but effective wastewater recycling is essential to minimize freshwater and nutrients consumption. Carbon dioxide from flue gas from power plants can be used for cultivating algae to facilitate optimal algae growth. However, CO_2 capture and pumping to the algae growing facility is costly and energy demanding (Judd et al 2015, Murphy 2017).

5.3.4 Biorefineries

The biorefinery concept is still in its infancy. However, the degree of maturity of the biorefinery concepts is very heterogeneous. Several biorefineries are in the early stages of commissioning and/or commercial production. Large scale implementation of highly-efficient advanced biorefineries is still a goal to be realised. This is caused by a variety of non-technical and technical barriers (IEA Bioenergy, IETS 2017).

Numerous technological challenges still hamper upscaling and commercial operation of biorefineries. The deployment of the new biorefineries depends on the technical maturity of a range of processes to produce biobased materials, biochemicals and energy, as well as on the extent of integration of different technologies and processes. Several biochemical and thermochemical conversion technologies are combined together to have more flexibility in product generation and to reduce the overall cost. However, major technical barriers include process integration and adaptation to variations in feedstock supply. There are technical knowledge gaps as many of the individual processes of biorefining are still not mature.

The scale of biorefineries is a major challenge. A biorefinery is a capital-intensive and faces large challenges for implementation due to high capital costs required and barriers for sustainable biomass supply. New biorefineries linked to existing oil refineries, petrochemical clusters or pulp and paper mills would take advantage of existing infrastructures (IEA Bioenergy, IETS 2017). Small-scale biorefineries will require a significantly lower investment and thus solve several challenges. Another important challenge is how to integrate new biorefineries into existing agro-industrial and agro-food processing value chains.

6 Conclusions & Recommendations

6.1 Biochemical processing

6.1.1 Anaerobic digestion

Anaerobic digestion is an established technology and to an extent demonstrated. There is still a need to improve **technical and economic viability** of biogas plants, especially of smaller plants, through better control and process optimisation. There should be a focus to **enlarge the feedstock base**, to process new and difficult to degrade substrates, such as lignocellulosic feedstocks, agri-residues, organic fraction of municipal solid waste, and sewage sludge. There if a need to R&D to improve the biological digestion process, to increase the loading rate and advance co-digestion, dry fermentation and thermophilic processes. There is the need to **improve biodegradability** and increase biogas yield, through hydrolysis pretreatment or enzymatic reactions, etc., and prove the viability of the use of new substrates, such as micro and macro algae. Biogas **upgrading** to biomethane should receive more attention to achieve technological improvements, to reduce energy intensity and improve cost performance that could lead to reducing energy production costs.

6.2 Thermochemical processing

6.2.1 Biomass combustion

Biomass combustion technology is available for heat and power production in commeraial operation. Further development on biomass combustion need to focus on the development and optimisation of better boiler designs and advanced control systems for **improving combustion systems,** increase efficiency and reduce the costs of energy generation. There is also a need to develop new **advanced systems**, with increased **fuel flexibility** to be able to use a wide feedstock range and higher conversion efficiencies (supercritical steam parameters), above the state of the art. There is a need for the development of low emission stoves and boiler systems and further reduce harmful emissions associated with small-scale use of biomass. An important issue is to make **better use of the heat** generated to improve the overall energy efficiency of the biomass plants and through better heating/cooling networks. There is also a need to develop cost-effective and high efficiency energy generation systems using low and medium-temperature **waste heat**. New hybrid systems could combine biomass, biogas with hydrogen production, PV or concentrated solar systems, heat pumps, micro gas turbine and fuel cells. There is a need to integrate, optimize and demonstrate such systems at large scale.

6.2.2 Torrefaction

Biomass torrefaction is a process proved at pilot scale and a number of demonstration and commercial facilities are in operation. Further development of torrefaction is needed to overcome certain technical and economic challenges and **scaling up** the process. There is a need for finding the **optimal configuration** and optimal **process conditions** for producing a stable and high quality end-product, using a broad feedstock range. The optimal conditions needs to be tailored depending on several factors, such as the type of feedstock, product specifications (size, torrefaction degree etc.), reactor technology and design, process control and heat integration. Future work should focus on integrated torrefaction and **densification** processes for the production of torrefied pellets and on integrated torrefaction and gasification for high-quality syngas production. R&D work should focus on the assessment of **end-use** performance, for assessing the handling, storage, safety and milling behaviour and combustion characteristics.

6.2.3 Pyrolysis

Previous research on pyrolysis has led to important developments in the pyrolysis process, reaching pre-commercial, demonstration stage. Future development is however needed to determine the best operating conditions, improve **reactor design** and achieve process **optimisation** to maximize bio-oil yield, increase process efficiency process and to increase process reliability and for broadening feedstock base for bio-oil. A key goal remains the improvement of the **bio-oil quality**, and consistency, through improved bio-oil **cleaning** and **upgrading** to allow its use in downstream processes (heat, power, chemicals, synthetic fuels, and biocrude production). **Improving** the pyrolysis processes, including catalytic pyrolysis, could increase pyrolysis oil composition and help overcome challenges for bio-oil upgrading. There is a need for the demonstration of a consistent and stable intermediate product suitable for downstream processes. Pyrolysis processes require scale-up and demonstration of bio-oil production technologies with different biomass feedstocks and mixtures.

6.2.4 Hydrothermal processing

Hydrothermal processes (hydrothermal carbonization, liquefaction and gasification) are promising processes that are able to convert a wide range of wet feedstocks into **bio-char**, **bio-oil** (bio-crude), or **gas** (e.g., hydrogen, methane). Hydrothermal liquefaction is of particular interest, producing a liquid that can be used as a bio-fuel and as a substitute for crude oil in multiple applications. There is a need for expanding the **understanding** of hydrothermal liquefaction and the knowledge-base on reaction mechanisms and process kinetics of HTL. There are research gaps with respect to **catalyst** performance, poisoning, loss, deactivation, regeneration and lifetime that are essential for their performance. Better understanding of HTL process is needed to identify specific challenges and to develop **equipment** able to operate in extreme temperature and pressure conditions. The greatest challenge yet to be addressed is to understand the impacts of feedstock composition and process conditions on bio-crude **product yield and quality**. Critical process data is needed from testing various feedstocks to analyse processing parameters to enable establishing reactor configuration and enable process optimisation. More techno-economic data is needed to enable large scale deployment.

6.2.5 Biomass gasification

Continuous R&D effort over the last years has led to significant progress, bringing biomass gasification to reaching demonstration stage. Although biomass gasification has seen significant developments over the last years and several projects have been implemented worldwide, biomass gasification needs **demonstration** at scale and requires significant **technological improvements**. Critical factors for gasification still need to be addressed, such as the low reliability, sensitivity to feedstock quality, the variability of gas composition, slagging, corrosion and agglomeration. There is still work to be done to prove continuous, **reliable long-term operation** of the different gasification systems at scale with a range of feedstocks. Key technical challenges and needs still include improving **process integration**, **monitoring and control**, **gas clean-up** and **gas upgrading**, improving performance and efficiency and reducing costs. Syngas cleaning and reforming is the biggest challenge in gasification due to the high content of impurities (particle, tar, alkali, chloride, ammonia, etc.), and the requirement for ultra-clean syngas for many downstream possible applications. Research should focus more on the **optimisation and improvement** of biomass gasification process, to improve gasifier design, operating conditions, new catalysts for gas conversion as well as on gas cleaning, upgrading, reforming process to obtain a clean syngas.

6.3 Algae for bioenergy

There is a large interest in developing algae production for various uses with many projects implemented worldwide. Algae cultivation for bioenergy production requires a combination of technical breakthroughs on **cultivation** under different locations-specific conditions. More research is needed on species characteristics to increase photosynthetic conversion efficiencies, to increase algae yields and energy content, to use/develop species that are resistant to a variety of conditions and less susceptible to contaminants/pathogens. Microlgae **harvesting** remains a critical challenge faced by algae cultivation and focus should be on harvesting, separation and dewatering processes (e.g. centrifugation, flocculation, separation) that require further development. There is a need for developing **large-scale cultivation** systems, for off-shore and farms/land-based ponds cultivation. There is also a need for demonstration at full scale of pre-treatment/hydrolysis processes, oil extraction and biochemical (anaerobic digestion, fermentation) and thermochemical (pyrolysis, hydrothermal liquefaction) **conversion** technologies.

6.4 Biorefineries

Biorefineries offer interesting perspectives for the integrated production of a range of biobased products and bioenergy. Biorefineries are largely at the conceptual stage, new products, routes and process configurations being currently developed. A general need is to **validate existing concepts** by scale-up to the commercial scale and to demonstrate the technologies and process chains. The most important challenge for the deployment of the new biorefinery concepts is the lack of large scale demonstration of various technologies to produce bio-based materials, bio-chemicals and energy, as well on their integration. Thus, biorefineries require further development of new and optimised biochemical and thermochemical conversion processes and the adaptation and optimisation of downstream processing within the biorefinery system. The implementation of biorefineries requires **further development** along the entire biorefinery value chain, optimising various integrated process, from pre-treatment and multiple conversion processes to final products following the cascade use principle. A key point is the **integration and adaptation** of biochemical processes to up-stream processes that can result in by-products that inhibit down-stream processes. Therefore, further research should focus on scale-up activities from pilot scale to demonstration scale and to prove viability in commercial operation.

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Acronyms and abbreviations

AD	Anaerobic digestion
BBI	Bio-based Industries
BETO	DOE Bioenergy Technologies Office
BIGCC	Biomass Integrated Gasification Combined Cycle
BIG-GT	Biomass Integrated Gas Turbine
BtL	Biomass to liquid
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CFBC	Circulating Fluidised Bed Combustion
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CP	Collaborative project
CPI	Current Policy Initiative Scenario
CPC	Coordinated Patent Classification
CSA	Coordination and Support Action
DH	District Heating
EC	European Commission
EIBI	European Industrial Bioenergy Initiative
ERC	European Research Council
ESP	ElectroStatic Precipitator
EU	European Union
FBC	Fluidised Bed Combustion
FP7	Seventh Framework Programme for Research and Technological Development
FT	Fischer-Tropsch
GHG	GreenHouse Gas
H2020	Horizon 2020 Programme
HTC	HydroThermal Carbonization
HTG	Hydrothermal Gasification
HTL	HydroThermal Liquefaction
IA	Innovation action
IEA	International Energy Agency
IED	Industrial Emissions Directive
IEE	Intelligent Energy Europe Programme

IGCC	Integrated Gasification Combined Cycle
IP	Implementation Plan
IPC	International Patent Classification
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
KPI	Key Performance Indicators
LCA	Life Cycle Analysis
LCEO	Low Carbon Energy Observatory
LCOE	Levelised Cost Of Electricity
LFG	LandFill Gas
LHV	Lower Heating Value
MRL	Manufacturing Readiness Level
MS	Member State
MSW	Municipal Solid Waste
NER	New Entrants' Reserve
NREAP	National Renewable Energy Action Plan
NREL	National Renewable Energy Laboratory
OPEX	Operational expenditure
ORC	Organic Rankine Cycles
PWS	Pressurised Water Scrubbing
PSA	Pressure Swing Adsorption
RED	Renewable Energy Directive
REN21	Renewable Energy Policy Network for the 21st Century
R&D	Research and Development
RIA	Research and Innovation action
SCR	Selective Catalytic Reduction
SET Plan	Strategic Energy Technology Plan
SETIS	Strategic Energy Technologies Information System
SNG	Synthetic Natural Gas
TRL	Technology Readiness Level
US	United States
US EPA	United States Environmental Protection Agency
US DOE	United States Department Of Energy
WID	Waste Incineration Directive
WtE	Waste-to-Energy

Annex 1. Cross-cutting bioenergy projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
BIOPROM	EIALT/EIE/04/100/2004	Altener RES	"Bioenergy-Promotion" - Overcoming the non-technical barriers of project-implementation for bioenergy in condensed urban environments	717,942	358,971	2005-01-01	2007-06-30
EUBIONETII	EIALT/EIE/04/065/2004	Altener Heating	Efficient trading of biomass fuels and analysis of fuel supply chains and business models for market actors by networking	1,238,466	619,233	2005-01-01	2007-12-31
QUALITY WOOD	EISAS/EIE/06/178/2006	Altener RES	Increased deployment of firewood by improving fuel quality and low emission combustion	761,857	380,929	2006-11-01	2009-04-30
BIOMASSTRADE CENTRES	EISAS/EIE/07/054/2007	Altener Biofuel	Supporting the organization of spot markets supply for wood chips and firewood	641,800	320,900	2007-11-01	2010-10-31
EUBIONET III	IEE/07/777	Altener Heating	Solutions for biomass fuel market barriers and raw material availability	1,822,119	1,366,589	2008-09-01	2011-08-31
CODE	IEE/07/564/SI2.499462	Altener Heating	Cogeneration Observatory and Dissemination Europe	1,100,279	825,209	2008-10-01	2011-03-31
Woodheat Solutions (WHS)	IEE/07/726/S12.499568	Altener Heating	Woodheat Solutions	972,450	729,338	2008-10-01	2011-03-31
BEN	IEE/07/595	Altener Biobusiness	Biomass energy register for sustainable site development for European Regions	1,398,731	1,049,048	2008-11-01	2011-10-31
BIOENERGIS	IEE/07/638/SI2.499702	Altener Biobusiness	GIS-based decision support system aimed at a sustainable energetic exploitation of biomass at regional level	1,482,186	933,777	2008-11-01	2011-10-31
MAKE-IT-BE	IEE/07/722	Altener Biobusiness	Decision Making and Implementation Tools for Delivery of Local & Regional Bio-Energy Chains	1,342,795	1,007,096	2008-11-01	2011-10-31
ENERCOM	218916	Collaborative project	Polygeneration of energy, fuels and fertilisers from biomass residues and sewage sludge	5,212,017	2,528,833	2008-11-03	2013-11-02
BIOMASS FUTURES	IEE/08/653	Altener Heating	Biomass role in achieving the Climate Change & Renewables EU policy Targets. Demand and Supply dynamics under the perspective of Stakeholders	1,490,386	1,117,790	2009-06-01	2011-12-31
FARMAGAS	IEE/08/625	Altener Biofuel	Biogas Production from Agricultural Wastes in European Farms	580,580	435,435	2009-06-01	2011-05-31
AGRIFORENERGY 2	IEE/08/600	Altener Biobusiness	Promoting and securing the production of biomass from forestry and agriculture without harming the food production	1,523,520	1,142,640	2009-07-01	2012-06-30
AFO	IEE/08/435	Altener Heating	Activating private forest owners to increase forest energy supply	1,411,848	1,058,886	2009-10-01	2012-09-30
BIOMOB	245449	Coordination action	Biomass Mobilisation	1,166,226	1,010,400	2009-12-01	2011-11-30
BIOGASIN	IEE/09/848	Altener Biofuel	Sustainable biogas market development in Central and Eastern Europe	1,508,188	1,131,141	2010-05-01	2012-10-31
BIOREGIONS	IEE/09/769	Altener Biobusiness	Regional Networks for the development of a Sustainable Market for Bioenergy in Europe	1,491,384	1,118,538	2010-05-01	2013-05-01
MIXBIOPELLS	IEE/09/758	Altener Biobusiness	Market Implementation of Extraordinary Biomass Pellets	977,752	733,314	2010-05-01	2012-06-30
FOREST	IEE/09/656/SI2.558320	Altener Biobusiness	FOsteRing Efficient long term Supply parTnerships	1,284,810	963,608	2010-05-27	2012-11-27

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
BIOENERGY FARM	IEE/09/637	Altener Biobusiness	Implementation plan for BioEnergy Farm	1,210,751	908,063	2010-06-01	2013-04-01
BIO-HEAT	IEE/09/890	Altener Heating	Promotion of Short Rotation Coppice for District Heating Systems in Eastern Europe	776,256	582,192	2010-09-01	2012-08-31
CROSSBORDERBIOENERGY	IEE/09/933	Altener Biobusiness	Cross-border markets for the European bioenergy industry	865,690	649,268	2010-09-01	2013-05-31
BIO-METHANE REGIONS	IEE/10/130	Altener Biofuel	Promotion of Bio-Methane and its Market Development through Local and Regional Partnerships	1,653,636	1,240,227	2011-04-01	2014-04-30
SOLIDSTANDARDS	IEE/10/218	Altener Biofuel	Enhancing the Implementation of Quality and Sustainability Standards and Certification Schemes for Solid Biofuels	1,353,106	1,014,830	2011-04-01	2014-03-31
BIOMASSTRADECENTREII	IEE/10/115	Altener Biofuel	Development of Biomass Trade and Logistics Centres for Sustainable Mobilisation of Local Wood Biomass Resources	1,580,683	1,185,512	2011-05-01	2014-04-30
BIOMASTER	IEE/10/351	Altener Biofuel	Biomethane as an Alternative Source for Transport and Energy Renaissance	2,471,189	1,853,392	2011-05-01	2014-04-30
GERONIMO II-BIOGAS	IEE/10/228	Altener Biofuel	A Focussed Strategy for Enabling European Farmers to Tap into Biogas Opportunities	1,755,936	1,316,952	2011-05-01	2013-10-31
PELLCERT	IEE/10/463	Altener Biofuel	European Pellet Quality Certification	901,623	676,217	2011-05-01	2014-04-30
URBANBIOGAS	IEE/10/251	Altener Biofuel	Urban Waste for Biomethane Grid Injection and Transport in Urban Areas	1,170,240	877,680	2011-05-01	2014-05-01
GreenGasGrids	IEE/10/235	Altener Biofuel	Boosting the European Market for Biogas Production, Upgrade and Feed-In into the Natural Gas Grid	1,998,129	1,498,597	2011-06-01	2014-05-31
PROMOBIO	IEE/10/470	Altener Biobusiness	Promotion to regional bioenergy initiatives	922,797	692,098	2011-06-01	2014-05-31
BRISK	284498	Combination of CP and CSA	The European Research Infrastructure for Thermochemical Biomass Conversion	11,046,379	8,980,957	2011-10-01	2015-09-30
BioGrace-II	IEE/11/733	Altener RES	Bioenergy Greenhouse gas emissions: Align Calculations in Europe	1,194,202	895,652	2012-04-01	2015-03-31
SUSTAINGAS	IEE/11/838	Altener Biofuel	Enhancing sustainable biogas production in organic farming	1,355,914	1,016,936	2012-04-01	2015-03-31
BIOGASHEAT	IEE/11/025	Altener Biofuel	Development of sustainable heat markets for biogas plants in Europe	1,361,271	1,020,953	2012-04-05	2015-04-04
CODE2	IEE-11-910	Altener Heating	Cogeneration Observatory and Dissemination Europe 2	0	0	2012-06-01	2015-12-01
BESTF	321477	CSA-ERA-Plus	Bioenergy sustaining the future: joint strategic planning and programming to enable the implementation of bioenergy demonstrations	10,112,529	3,337,135	2013-01-01	2017-12-31
BASIS	IEE/12/830	Altener Biofuel	Biomass Availability and Sustainability Information System	975,936	731,952	2013-04-01	2016-03-31
BIOEUPARKS	IEE/12/994	Altener Biobusiness	Exploiting the potentialities of solid biomasses in EU Parks	1,333,071	999,803	2013-04-01	2016-03-31
BIOMASSPOLICIES	IEE/12/835	Altener Biofuel	Strategic Initiative for Resource Efficient Biomass Policies	2,032,636	1,524,477	2013-04-01	2016-03-31
BIOTEAM	IEE/12/842	Altener RES	Optimizing Pathways and Market Systems for Enhanced Competitiveness of Sustainable Bio-Energy	1,523,560	1,142,670	2013-04-01	2016-03-31
EPIC2020	IEE/12/807	Altener Biofuel	Symbiotic bio-Energy Port Integration with Cities by 2020	1,928,423	1,446,317	2013-04-01	2016-03-31
FABBIOGAS	IEE/12/768	Altener Biobusiness	BIOGAS production from organic waste in the European Food And Beverage industry	1,105,045	828,784	2013-04-01	2015-09-30

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
GR3	IEE/12/046	Altener Biofuel	GRass as a GReen Gas Resource: Energy from landscapes by promoting the use of grass residues as a renewable energy resource	1,572,705	1,179,529	2013-04-01	2016-03-31
S2BIOM	608622	Collaborative project	Delivery of sustainable supply of non-food biomass to support a "resource-efficient" Bioeconomy in Europe	5,161,511	3,999,629	2013-09-01	2016-08-31
BESTF2	618046	CSA-ERA-Plus	Bioenergy sustaining the future 2	24,343,283	7,043,283	2013-12-01	2018-11-30
BIOENERGY FARM II	IEE-13-683-SI2.675767	Altener Biobusiness	Manure, the sustainable fuel for the farm	1,869,679	1,402,259	2014-03-01	2016-12-31
SRCPLUS	IEE-13-574	Altener Bioenergy	Short Rotation Woody Crops (SRC) plantations for local supply chains and heat use	1,353,230	1,014,923	2014-03-01	2017-02-28
BIOGAS3	IEE-13-477	Altener Bioenergy	Sustainable Small-scale biogas production from agro-food waste for energy Self-sufficiency		1,140,000	2014-06-16	2015-01-16
BIOTRADE2020PLUS	IEE-13-577	Altener Bioenergy	Supporting a Sustainable European Bioenergy Trade Strategy			2014-06-20	2015-01-20
SUCELLOG	IEE-13-638	Altener Bioenergy	Triggering the Creation of Biomass Logistic Centres by the Agro-Food Sector		1,370,000	2014-06-20	2015-01-20
Bioenergy4Business	646495	Coordination and support action	Uptake of Solid Bioenergy in European Commercial Sectors (Industry, Trade, Agricultural and Service Sectors) – Bioenergy for Business	1,540,714	1,540,714	2015-01-01	2017-08-31
BioRES	645994	Coordination and support action	Sustainable Regional Supply Chains for Woody Bioenergy	1,865,411	1,865,411	2015-01-01	2017-06-30
greenGain	646443	Coordination and support action	Supporting Sustainable Energy Production from Biomass from Landscape Conservation and Maintenance Work	1,829,391	1,829,391	2015-01-01	2017-12-31
MOBILE FLIP	637020	Innovation action	Mobile and Flexible Industrial Processing of Biomass	9,698,843	8,606,175	2015-01-01	2018-12-31
BioValue	666644	SME instrument phase 2	Quality determination of solid biofuels in real time	2,335,550	1,634,885	2015-03-01	2018-05-31
DIABOLO	633464	Research and Innovation action	Distributed, integrated and harmonised forest information for bioeconomy outlooks	4,998,970	4,734,595	2015-03-01	2019-02-28
FACCE SURPLUS	652615	ERA-NET Cofund	SUstainable and Resilient agriculture for food and non-food systems	15,151,515	5,000,000	2015-03-01	2020-02-29
SECURECHAIN	646457	Coordination and support action	Securing future-proof environmentally compatible bioenergy chains	1,809,586	1,809,586	2015-04-01	2018-03-31
Amicrex	661198	Marie Curie Individual Fellowships	Development of a Microwave Assisted Cell Disruption of Biomass and Extraction of Valuable Compounds	171,461	171,461	2015-05-01	2019-09-17
BioEnergyTrain	656760	Coordination and support action	BioEnergyTrain	3,697,580	3,697,579	2015-05-01	2019-04-30
ICRI-BIOM	664386	SGA CSA	International Centre for Research on Innovative Bio-based Materials	494,375	494,375	2015-06-01	2016-05-31
BESTF3	691637	ERA-NET Cofund	Bioenergy Sustaining the Future (BESTF) 3	6,477,369	2,137,532	2016-01-01	2020-12-31
Biomasud Plus	691763	Coordination and support action	Developing the sustainable market of residential Mediterranean solid biofuels.	1,971,610	1,971,610	2016-01-01	2018-12-31
CoolHeating	691679	Coordination and support action	Market uptake of small modular renewable district heating and cooling grids for communities	1,644,340	1,644,340	2016-01-01	2018-12-31
ERIFORE	654371	Coordination and support action	Research Infrastructure for Circular Forest Bioeconomy	2,630,950	2,628,700	2016-01-01	2018-01-31

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
FORBIO	691846	Coordination and support action	Fostering Sustainable Feedstock Production for Advanced Biofuels on underutilised land in Europe	1,941,581	1,941,581	2016-01-01	2018-12-31
SEEMLA	691874	Coordination and support action	Sustainable exploitation of biomass for bioenergy from marginal lands in Europe	1,629,884	1,629,884	2016-01-01	2018-12-31
WASTE2FUELS	654623	Research and Innovation action	Sustainable production of next generation biofuels from waste streams	5,989,744	5,989,743	2016-01-01	2018-12-31
AGRIFORVALOR	696394	Coordination and support action	Bringing added value to agriculture and forest sectors by closing the research and innovation divide	1,997,416	1,997,416	2016-03-01	2018-08-31
BestRES	691689	Coordination and support action	Best practices and implementation of innovative business models for Renewable Energy aggregatorS	1,994,813	1,994,813	2016-03-01	2019-02-28
BioVill	691661	Coordination and support action	Bioenergy Villages (BioVill) - Increasing the Market Uptake of Sustainable Bioenergy	1,998,918	1,998,918	2016-03-01	2019-02-28
InnoPellet	711540	SME instrument phase 2	Self-supporting biofuel sludge pellet producing system for small and medium sized sewage plants	2,158,500	1,510,950	2016-03-01	2018-10-31
uP_running	691748	Coordination and support action	Take-off for sustainable supply of woody biomass from agrarian pruning and plantation removal	1,992,920	1,992,920	2016-04-01	2019-06-30
EFFORTE	720712	BBI Research and Innovation action	Efficient forestry by precision planning and management for sustainable environment and cost-competitive BBI	4,203,421	2,230,221	2016-09-01	2019-08-31
ETIP Bioenergy-SABS	727509	Coordination and support action	European Technology and Innovation Platform Bioenergy – Support of Advanced Bioenergy Stakeholders 2016-17	599,105	599,105	2016-09-01	2018-08-31
BIOWAYS	720762	BBI Coordination and Support action	Increase public awareness of bio-based products and applications supporting the growth of the EU bioeconomy	965,750	965,750	2016-10-01	2018-09-30
GreenCarbon	721991	Marie Curie European Training Networks	Advanced Carbon Materials from Biowaste: Sustainable Pathways to Drive Innovative Green Technologies	3,623,224	3,623,224	2016-10-01	2020-09-30
AGROinLOG	727961	Innovation action	Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe	6,385,661	5,935,715	2016-11-01	2020-04-30
Ambition	731263	Research and Innovation action	Advanced biofuel production with energy system integration	2,494,986	2,494,986	2016-12-01	2019-11-30
BIOREG	727958	Coordination and support action	Absorbing the Potential of Wood Waste in EU Regions and Industrial Bio-based Ecosystems	996,056	996,056	2017-01-01	2019-12-31
BRISK II	731101	Research and Innovation action	Biofuels Research Infrastructure for Sharing Knowledge II	9,977,271	9,968,144	2017-05-01	2022-04-30
STAR-ProBio	727740	Research and Innovation action	Sustainability Transition Assessment and Research of Bio-based Products	5,306,372	4,983,872	2017-05-01	2020-04-30
GRACE	745012	BBI Innovation action - Demo	GRowing Advanced industrial Crops on marginal lands for biorEfineries	15,000,851	12,324,633	2017-06-01	2022-05-31
SYSTEMIC	730400	Innovation action	Systemic large scale eco-innovation to advance circular economy ^mineral recovery from organic waste in Europe	9,723,586	7,859,829	2017-06-01	2021-05-31
EcoBioMass	768291	SME instrument phase 2	EcoBioMass – harvesting forest energy biomass in the 21st century	1,856,500	1,299,550	2017-08-01	2019-07-31
ADVANCEFUEL	764799	Coordination and support action	Facilitating market roll-out of RESfuels in the transport sector to 2030 and beyond	2,628,246	2,628,246	2017-09-01	2020-08-31
ENABLING	774578	Coordination and support action	Enhance New Approaches in BioBased Local Innovation Networks for Growth	1,997,640	1,997,640	2017-12-01	2020-11-30
FIBRENET	764713	Marie Curie European	A Training Network on Designing Novel Bio-based Fibre	3,832,629	3,832,629	2017-12-01	2021-11-30

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
		Training Networks	Products for Targeted Advanced Properties and New Applications				
BIOVOICES	774331	Coordination and support action	Mobilization of a plurality of voices and mutual learning to accelerate the Bio-based sector	2,996,428	2,996,428	2018-01-01	2020-12-31

Annex 2. Anaerobic digestion projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
BIOPROFARM	EISAS/EIE/05/086/2005	Altener Small scale	Promotion of biomethanisation in agricultural environment as a decentralised renewable energy resource for Europe	523,174	261,587	2006-01-01	2007-12-31
GERONIMO	EISAV/07/220/S12.466709	SAVE Industry	Getting energy reduction on agendas in industrial manufacturing operations	1,152,444	576,222	2007-10-01	2009-09-30
ANAMIX	230829	MC International Research Staff Exchange Scheme	A two year exchange programme on ANAerobic MIXed cultu-res to study and improve biological generation of chemicals and energy carriers from organic residues		68,400	2009-01-01	2010-12-31
FARMAGAS	IEE/08/625	Altener Biofuels	Biogas production from agricultural wastes in European farms	580,580	435,435	2009-06-01	2011-05-31
PLASMANURE	232267	Research for SMEs	Novel plasma-catalyst reactor for the total conversion of the ammonia contained in pig manure into environmental neutral products	1,327,435	950,240	2010-02-01	2012-04-30
VALORGAS	241334	Collaborative project	Valorisation of food waste to biogas	4,657,517	3,485,462	2010-03-01	2013-08-31
SMART TANK	262241	Research for SMEs	Farm and Agriculture Stabilised Thermophilic Anaerobic Digestion	1,016,074	799,462	2010-12-01	2013-02-28
3CBIOTECH	261330	ERC-SG - ERC Starting Grant	Cold Carbon Catabolism of Microbial Communities under-prinning a Sustainable Bioenergy and Biorefinery Economy	1,499,797	1,499,797	2011-05-01	2016-04-30
GERONIMO II-BIOGAS	IEE/10/228	Altener Biofuels	A focussed strategy for enabling European farmers to tap into biogas opportunities	1,755,936	1,316,952	2011-05-01	2013-10-31
ROUTES	265156	SME focused research project	Novel processing routes for effective sewage sludge management	4,850,183	3,364,600	2011-05-01	2014-04-30
GREENGASGRIDS	IEE/10/235	Altener Biofuels	Boosting the European market for biogas production, upgrade and feed-In into the natural gas grid	1,998,129	1,498,597	2011-06-01	2014-05-31
AD-WINE	286052	MC Industry-Acade-mia Partnerships	High performance Anaerobic digesters for the treatment of medium size wineries' effluents	777,706	777,706	2011-12-01	2015-11-30
BIOWET	269255	MC Int. research staff exchange scheme	Advanced Biological Waste-to-Energy Technologies	256,300	249,900	2012-01-01	2015-12-31
LTANITRO	297436	Supporting action	Low-temperature anammox for nitrogen removal	166,280	150,000	2012-03-01	2013-02-28
INEMAD	289712	Collaborative Project	Improved nutrient and energy management through anaerobic digestion	3,875,356	2,961,624	2012-04-01	2016-03-31
SUSTAINGAS	IEE/11/838	Altener biofuels	Enhancing sustainable biogas production in organic farming			2012-04-01	2015-03-31
BIOGASHEAT	IEE/11/025	Altener biofuels	Development of sustainable heat markets for biogas plants in Europe	1,361,271	1,020,953	2012-04-05	2015-04-04
SOLROD	IEE/11/MLEI/080	Altener Heating	Solrod Biogas Plant Investment Project	637,499	478,124	2012-06-01	2014-05-31
WAVALUE	304435	CIP-Eco-Innovation	High Added Value Ecofertilizers from Anaerobic Digestion Effluent Wastes	1,842,666	921,333	2012-07-01	2014-12-31
F2W2F	304388	CIP-EIP Eco-	Food to Waste to Food	1,636,916	817,020	2012-08-01	2015-07-31

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
		Innovation					
ORION	282693	Research for SMEs associations	Organic waste management by a small-scale Innovative automated system of anaerobic digestion	3,880,501	2,978,002	2012-08-01	2015-07-31
AD-WISE	315115	Research for SMEs	Automated system based on on-line VFA sensors for an optimised control of anaerobic digestion plants	1,257,346	939,000	2012-09-01	2014-11-30
BIOMAN	315664	Research for SMEs	Economically efficient biogas production from manure fibres and straw	1,849,792	1,387,997	2012-10-01	2015-06-30
BIOWASTE4SP	312111	Res proj for specific cooperation actions	Turning biowaste into sustainable products: development of appropriate conversion technologies in developing countries	3,885,598	2,992,555	2012-10-01	2015-09-30
WASTE2GO	308363	Collaborative project	Development and verification of an innovative full life sustainable approach to the valorisation of municipal solid waste into industrial feedstocks	4,588,640	3,495,426	2012-10-01	2015-09-30
THERCHEM	315630	Research for SMEs	Thermochemical pre-treatment technology for residues from breweries and other biomass to enhance anaerobic digestion	1,046,544	712,000	2012-11-01	2014-12-31
ADAW	314867	BSG-SME - Research for SMEs	Saponification pre-treatment and biosensors based control system for slaughterhouse waste AD improvement	1,435,252	1,086,000	2013-03-01	2015-02-28
FABBIOGAS	IEE/12/768	Altener Biobusiness	Biogas production from organic waste in the European food and beverage industry	1,105,045	828,784	2013-04-01	2015-09-30
GR3	IEE/12/046	Altener Biofuels	Grass as a green gas resource: energy from landscapes by promoting the use of grass residues as a RES	1,572,706	1,179,529	2013-04-01	2016-03-31
BIOROBUR	325383	JTI-CP-FCH - Collaborative Project	Biogas robust processing with combined catalytic reformer and trap	3,843,868	2,486,180	2013-05-01	2016-04-30
WASTE2BIOHY	326974	Marie Curie Intra-European Fellowships	Sustainable hydrogen production from waste via two-stage bioconversion process: an eco-biotechnological approach	194,047	194,047	2013-06-01	2015-05-31
ATBEST	316838	Marie-Curie Initial Training Networks	Advanced Technologies for Biogas Efficiency Sustainability and Transport	3,864,394	3,864,394	2013-07-01	2017-06-30
OPTI-VFA	606096	Research for SMEs	Novel monitoring and process control system for efficient production of VFA and biogas in anaerobic digestion plant	1,487,698	1,149,995	2013-09-01	2015-08-31
BIFFIO	605815	Research for SME Associations	Cooperation between the aquaculture & agriculture sectors with the intent to use animal manure and fish faeces for sus-tainnable production and utilization of RE&recovered nutrients	2,321,524	1,745,264	2013-11-01	2016-10-31
CONDIMON	606080	Research for SMEs	Development of an in-line multi-parameter oil condition monitoring system including a novel oil corrosion sensor for bio-gas operated power generator engines	1,284,226	908,000	2013-11-01	2015-10-31
NUTREC	606057	Research for SMEs	Green nutrients recovery systems	1,008,840	783,000	2013-11-01	2016-04-30
LEGUVAL	315241	Research for SME associations	Valorisation of legumes co-products and by-products for package application and energy production from biomass	2,459,737	1,777,874	2013-12-01	2016-11-30
PLASCARB	603488	Collaborative project	Innovative plasma based transformation of food waste into high value graphitic carbon and renewable hydrogen	4,840,521	3,784,739	2013-12-01	2016-11-30
MICRODE	336355	ERC Starting Grant	Interpreting the irrecoverable microbiota in digestive ecosystems	1,467,176	1,467,176	2014-02-01	2019-01-31
Bioenergy Farm II	IEE-13-683-SI2.675767	Altener Biobusiness	Manure, the sustainable fuel for the farm	1,869,679	1,402,259	2014-03-01	2016-12-31
BIOGAS3	IEE-13-477	Altener Bioenergy	Sustainable small-scale biogas production from agro-food waste for energy self-sufficiency			2014-06-16	2015-01-16

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
PHASEPLIT	602007	Research for SMEs	Two-phase Acid/Gas Anaerobic Reactor for Industrial Wastewater of Food & Drink SME industries	1,483,869	1,124,000	2014-09-01	2016-08-31
Bin2Grid	646560	Coordination and support action	Turning unexploited food waste into biomethane supplied through local filling stations network	709,469	709,468	2015-01-01	2017-12-31
BIOSURF	646533	Coordination and support action	BIomethane as sustainable and renewable fuel	1,872,912	1,872,912	2015-01-01	2018-01-01
ADD-ON	666427	SME instrument Ph. 2	A demonstration plant of enhanced biogas production with Add-On technology	2,021,078	1,414,754	2015-03-01	2018-07-31
Bio-HyPP	641073	Research and Innovation action	Biogas-fired Combined Hybrid Heat and Power Plant	5,775,869	5,775,869	2015-06-01	2019-05-31
The Exergyn Drive	672528	SME instrument Ph. 2	The Exergyn Drive™ – an engine that runs on hot water	3,547,219	2,483,053	2015-06-01	2017-05-31
POWERSTEP	641661	Innovation action	Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration	5,173,855	3,997,126	2015-07-01	2018-06-30
PHARM AD	661427	Marie Curie Individual Fellowships	Removal of pharmaceutical micropollutants from wastewater by AD and its effect on N recovery from digestate by microalga	183,455	183,455	2015-08-01	2017-07-31
BIONICO	671459	FCH2-RIA - Research and Innovation action	BIOgas membrane reformer for deceNtralIzed hydrogen produCtiOn	3,396,640	3,147,640	2015-09-01	2019-02-28
DEMOSOFC	671470	FCH2-IA - Innovation action	DEMOnstration of large SOFC system fed with biogas from WWTP	5,905,336	4,492,561	2015-09-01	2020-08-31
H2AD-aFDPI	698374	SME instrument Ph. 2	Innovative and scalable biotechnology using Microbial Fuel Cell and AD for the treatment of micro-scale industrial & agriculture effluents to recover energy from waste	3,054,206	2,137,944	2015-11-01	2017-10-31
BiogasAction	691755	Coordination and support action	BiogasAction: Promotion of sustainable biogas production in EU	1,999,885	1,999,885	2016-01-01	2018-12-31
ISAAC	691875	Coordination and support action	Increasing Social Awarness and ACceptance of biogas and biomethane	1,480,535	1,480,535	2016-01-01	2018-06-30
ISABEL	691752	Coordination and support action	Triggering Sustainable Biogas Energy Communities through Social Innovation	1,897,438	1,897,438	2016-01-01	2018-12-31
OptiMADMix	658855	Marie Curie Individual Fellowships	Optimized Mesophilic Anaerobic Digestion Mixing	183,455	183,455	2016-01-05	2018-01-04
Lt-AD	718212	SME instrument Ph. 2	Low-temperature Anaerobic Digestion treatment of low-strength wastewaters	2,418,815	1,693,171	2016-06-01	2018-05-31
VicInAqua	689427	Research and Innovation action	Integrated aquaculture based on sustainable water recirculating system for the Victoria Lake Basin (VicInAqua)	2,997,710	2,997,710	2016-06-01	2019-05-31
DEMETER	720714	BBI Innovation action - Demonstration	Demonstrating more efficient enzyme production to increase biogas yields	6,610,040	4,629,586	2016-08-01	2019-07-31
SHEPHERD	731695	SME instrument Ph. 2	Energy-Efficient Activated Sludge Monitoring for Wastewater Treatment Plants	2,508,750	1,756,125	2016-08-01	2018-07-31
PROMETHEUS-5	733099	SME instrument Ph. 2	Energy efficient and environmentally friendly multi-fuel po-wer system with CHP capability for stand-alone application	1,731,996	1,212,397	2016-09-01	2019-02-28
BIOROBURPLUS	736272	FCH2-RIA - Research and Innovation action	Advanced direct biogas fuel processor for robust and cost-effective decentralised hydrogenproduction	3,813,536	2,996,249	2017-01-01	2020-06-30
HOMEBIOGAS	777770	SME instrument Ph. 2	Turning food industry's organic wastw into value	2,292,500	1,604,750	2017-08-01	2019-07-31
VEGWAMUS	751052	Marie Curie Individual	Developing commercial mushroom and vegetable product-ion	196,400	196,400	2017-10-01	2019-09-30

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
CIRCROP		Fellowships	in an integrated food to waste to food biosystem				
BIOGASTIGER	783727	SME instrument Ph. 2	BIOGASTIGER® system – turning global organic waste streams into smart and clean energy	3,043,375	2,130,363	2017-11-01	2019-10-31
ENGICOIN	760994	RIA - Research and Innovation action	Engineered microbial factories for CO2 exploitation in an integrated waste treatment platform	6,986,910	6,986,910	2018-01-01	2021-12-31
NTPLEASURE	748196	Marie Curie Individual Fellowships	Non-Thermal PLasma Enabled cAtalysis-Separation system for UpgRading biogasto mEthane-NTPleasure	195,455	195,455	2018-01-15	2020-01-14
Record Biomap	691911	Coordination and support action	Research Coordination for a Low-Cost Biomethane Production at Small and Medium Scale Applications	499,922	499,922		2016-04-01

Annex 3. Biomass combustion projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
DEBCO	218968	Collaborative project	Demonstration of large scale biomass co-firing and supply chain integration	6,941,512	4,166,823	2008-01-01	2012-12-31
BIOLIQUIDS-CHP	227303	Collaborative project	Engine and turbine combustion of bioliquids for combined heat and power production	4,309,697	1,602,318	2009-01-01	2011-12-31
FLEXI BURN CFB	239188	Collaborative project	Development of High Efficiency CFB Technology to Provide Flexible Air/Oxy Operation for Power Plant with CCS	10,851,767	6,413,869	2009-09-01	2013-02-28
ENERCORN	239476	Collaborative project	Demonstration of a 16MW high energy efficient corn stover biomass power plant	10,820,598	5,945,408	2009-12-01	2013-11-30
RECOMBIO	239530	Collaborative project	Recovered Fuels combined with Biomass	6,382,396	4,040,074	2010-01-01	2013-12-31
GREENEST	247322	ERC Advanced Grant	Gas turbine combustion with reduced emissions employing extreme steam injection	3,137,648	3,137,648	2010-07-01	2016-06-30
SUNSTORE 4	249800	Collaborative project	Innovative,multi-applicable-cost efficient hybrid solar and biomass energy large scale (district) heating system with long term heat storage and organic Rankine cycle electricity production	15,102,351	6,127,548	2010-07-01	2014-06-30
LOVE	256790	Collaborative project	Low temperature heat valorisation towards electricity production	5,061,352	3,299,789	2010-10-01	2014-03-31
EU-ULT RALOWDUST	268189	Collaborative project	Next generation small-scale biomass combustion technologies with ultra-low emissions	4,229,951	2,884,995	2011-01-01	2014-03-31
MACPLUS	249809	Collaborative project	Component performance-driven solutions for long-term efficiency increase in ultra supercritical power plants	18,204,522	10,704,675	2011-01-01	2015-06-30
BIOMAXEFF	268217	Collaborative project	Cost efficient biomass boiler systems with maximum annual efficiency and lowest emissions	6,726,662	4,238,559	2011-04-15	2014-10-14
BioCAT	286978	Research for SMEs	Clean Air Technology for Biomass Combustion Systems	1,410,933	1,004,500	2011-11-01	2013-10-31
FOUNDENERGY	285954	Research for SME	Waste heat recovery power generation based on ORC technology in foundry industry	3,336,811	2,599,500	2011-12-01	2014-11-30
ASHMELT	287062	Research for SME	Development of a practical and reliable ash melting test for biomass fuels, in particular for wood pellets	2,021,975	1,455,400	2012-01-01	2014-12-31

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
ICARUS	713514	Support actions	An innovative, environmentally friendly CO2/lubricant absorption power system for highly efficient power generation from low temperature industrial waste heat to reduce emissions and costs	1,422,302	1,110,000	2012-08-01	2014-07-31
HRC POWER	309006	Collaborative project	Hybrid renewable energy converter for continuous and flexible power production	3,101,969	2,383,041	2012-11-01	2016-04-30
BIOCHARISMA	333784	Marie-Curie Career Integration Grants	Sustainable use of Biochar in Mediterranean Agriculture	75,000	75,000	2013-03-01	2016-02-29
UP-THERM	605826	Research for SMEs	Innovative high efficiency phase change fluid based heat engine	1,481,256	1,081,641	2013-09-01	2015-10-31
BIOCHIPFEEDING	606464	Research for SMEs	Wood chip feeding technology of the future for small-scale biomass boilers	1,504,699	1,094,105	2013-10-01	2015-09-30
SYNGAS	330316	Marire Curie Intra-European Fellowships	Numerical Characterization and Modelling of Syngas Combustion	231,283	231,283	2013-10-21	2015-10-20
PITAGORAS	314596	Collaborative project	Sustainable urban planning with Innovative and low energy thermal and power generation from residual and renewable sources	14,357,144	8,364,786	2013-11-01	2017-10-31
MefCO2	637016	Innovation action	Synthesis of methanol from captured carbon dioxide using surplus electricity	11,041,537	8,622,293	2014-12-01	2018-11-30
TASIO	637189	Research and Innovation action	Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries	3,989,248	3,989,248	2014-12-01	2018-11-30
ORC-PLUS	657690	Innovation action	Organic Rankine Cycle - Prototype Link to Unit Storage	7,297,149	6,249,316	2015-05-01	2019-04-30
Bio-HyPP	641073	Research and Innovation action	Biogas-fired Combined Hybrid Heat and Power Plant	5,775,869	5,775,869	2015-06-01	2019-05-31
HPC4E	689772	Research and Innovation action	HPC for Energy	1,998,176	1,998,176	2015-12-01	2017-11-30
Residue2Heat	654650	Research and Innovation action	Renewable residential heating with fast pyrolysis bio-oil	5,466,479	5,465,728	2016-01-01	2019-12-31
TUCLA	669466	ERC-ADG - Advanced Grant	Towards a deepened understanding of combustion processes using advanced laser diagnostics	2,442,000	2,442,000	2016-01-01	2020-12-31
HYBURN	682383	ERC-COG - Consolidator Grant	Enabling Hydrogen-enriched burner technology for gas turbines through advanced measurement and simulation	1,996,135	1,996,135	2016-06-01	2021-05-31
MILESTONE	695747	ERC-ADG - Advanced Grant	Multi-Scale Description of Non-Universal Behavior in Turbulent Combustion	2,499,884	2,499,884	2016-06-01	2021-05-31
Biofficiency	727616	RIA - Research and Innovation action	Highly-efficient biomass CHP plants by handling ash-related problems	4,603,760	4,603,760	2016-11-01	2019-10-31
NanoORC	704201	Marie Curie EF-ST - Standard EF	Nanofluids as working fluids for organic Rankine cycles	200,195	200,195	2017-03-01	2020-02-28
CYCLOMB	760551	Innovation action	Disruptive Cyclone-based technology for effective and affordable particulate matter emission reduction in biomass combustion systems	1,640,774	1,241,826	2017-04-01	2019-03-31
VADEMECOM	714605	ERC-STG - Starting Grant	VAlidation driven DEvelopment of Modern and Efficient COMbustion technologies	1,499,110	1,499,110	2017-04-01	2022-03-31

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
START	785217	Innovation action	inveSTigation of an ultrA compact Reverse flow combusTor	640,868	640,868	2018-02-01	2020-01-31

Annex 4. Biomass torrefaction projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
SECTOR	282826	Collaborative project	Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction	10,288,836	7,565,725	2012-01-01	2015-06-30
PYROCHAR	603394	Research for SMEs	Pyrolisis based process to convert small WWTP sewage sludge into useful biochar	1,499,697	1,140,000	2013-11-01	2015-10-31
SteamBio	636865	Innovation action	Flexible Superheated Steam Torrefaction and Grinding of Indigenous Biomass from Remote Rural Sources to Produce Stable Densified Feedstocks for Chemical and Energy Applications	6,979,982	5,829,783	2015-02-01	2018-07-31
TORERO	745810	Innovation action	TORrefying wood with Ethanol as a Renewable Output: large-scale demonstration	15,849,490	11,472,916	2017-05-01	2020-04-30

Annex 5. Biomass pyrolysis projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
MICROFUEL	218454	Research for SME associations	Mobile Microwave Pyrolysis Plant turns Biomass into Fuel Locally	2,883,227	2,280,870	2009-01-01	2012-05-31
EMPYRO	239357	Collaborative project	Polygeneration through pyrolysis: Simultaneous production of fuel oil, process steam, electricity and organic acids	9,155,978	4,949,947	2009-12-01	2013-11-30
BIOFUEL	247550	MC International research staff exchange scheme	Biofuels from solid wastes	108,000	93,600	2010-10-01	2013-03-31
BIOBOOST	282873	Collaborative project	Biomass based energy intermediates boosting biofuel production	7,097,299	5,088,531	2012-01-01	2015-06-30
PYROGAS	286244	MC Industry-Academia Partnerships	The integration of intermediate pyrolysis and vapour gasification to create and effective and efficient biomass-to-energy system for combined heat and power	1,082,575	1,082,575	2012-04-01	2016-03-31
BIOECOSIM	308637	Collaborative project	An innovative bio-economy solution to valorise livestock manure into a range of stabilised soil improving materials for environmental sustainability and economic benefit for European agriculture	5,274,523	3,843,073	2012-10-01	2016-09-30
ENV-BIO	318927	MC International research staff exchange scheme	Technical and environmental analysis of advanced strategies for the energy valorisation of biomass	302,400	302,400	2013-01-01	2016-12-31
BIOGO-FOR-PRODUCTION	604296	Large-scale integrating project	Catalytic partial oxidation of bio gas and reforming of pyrolysis oil (bio oil) for an autothermal synthesis gas production and conversion into fuels	12,340,232	9,037,287	2013-12-01	2017-11-30
FLEXI-PYROCAT	643322	MC Research and Innovation Staff Exchange	Development of flexible pyrolysis-catalysis processing of waste plastics for selective production of high value products through research and innovation	634,500	405,000	2015-01-01	2018-12-31
PYROCHEM	656967	Marie Curie Individual Fellowship	Biopolymers 13C tracking during fast pyrolysis of biomass-A 2-level mechanistic investigation	183,455	183,455	2015-10-01	2017-09-30
Residue2Heat	654650	Research and Innovation action	Renewable residential heating with fast pyrolysis bio-oil	5,466,479	5,465,728	2016-01-01	2019-12-31
Bio4Products	723070	Innovation action	4x4, demonstrating a flexible value chain to utilize biomass functionalities in the processing industry	6,129,830	4,335,393	2016-09-01	2020-08-31
TO-SYN-FUEL	745749	Innovation action	The Demonstration of Waste Biomass to Synthetic Fuels and Green Hydrogen	14,511,923	12,250,528	2017-05-01	2021-04-30
HEAT-TO-FUEL	764675	Research and Innovation action	Biorefinery combining HTL and FT to convert wet and solid organic, industrial wastes into 2nd generation biofuels with highest efficiency	5,896,988	5,896,988	2017-09-01	2021-08-31
ECOCAT	752941	Marie Curie Individual Fellowship	Improving the economic feasibility of the biorefinery through catalysis engineering: enhancing the catalyst performance and optimizing valuable product yields	183,455	183,455	2018-01-15	2020-01-14

Annex 6. Hydrothermal processing projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
EUROCHAR	265179	SME focused research project	Biochar for carbon sequestration and large-scale removal of greenhouse gases (GHG) from the atmosphere	3,502,535	2,498,900	2011-01-01	2014-06-30
NEWAPP	605178	Research for SME associations	New technological applications for wet biomass waste stream products	2,580,062	1,756,000	2013-11-01	2016-04-30
Hydrofaction	666712	SME instrument phase 2	Resource and Cost Effective Conversion of Biomass to HydrocarbonTM Oil	2,631,166	1,841,816	2015-04-01	2017-03-31
HTC4WASTE	684143	SME instrument phase 2	Up-scaling, demonstration and first market application of Loritus' patented hydrothermal carbonisation as an eco-efficient and cost-effective organic waste processing technology	3,523,733	2,466,613	2015-11-01	2017-10-31
NewCat4Bio	751774	Marie Curie Individual Fellowship	Innovative sol-gel strategies for the production of homogeneous, hydrothermally stable, andporous mixed metal oxide catalysts for biomass conversion applications	172,800	172,800	2017-08-01	2019-07-31
HEAT-TO-FUEL	764675	RIA - Research and Innovation action	Biorefinery combining HTL and FT to convert wet and solid organic, industrial wastes into 2nd generation biofuels with highest efficiency	5,896,988	5,896,988	2017-09-01	2021-08-31
HYFLEXFUEL	764734	RIA - Research and Innovation action	Hydrothermal liquefaction: Enhanced performance and feedstock flexibility for efficient biofuel production	5,038,344	5,038,344	2017-10-01	2021-09-30

Annex 7. Biomass gasification projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
GREENSYNGAS	213628	SME focused research project	Advanced Cleaning Devices for Production of Green Syngas	4,089,167	2,718,461	2008-01-01	2011-02-28
UNIQUE	211517	SME focused research project	High purity syngas from biomass	3,721,305	2,693,628	2008-01-01	2010-12-31
POLYSTABILAT	219062	Collaborative project	Polygeneration through gasification utilising secondary fuels derived from MSW	7,563,452	4,269,804	2008-10-17	2015-04-16
H2-IGCC	239349	Collaborative project	Low Emission Gas Turbine Technology for Hydrogen-rich Syngas	17,191,878	11,279,696	2009-11-01	2014-04-30
BIOFUEL	247550	MC International research staff exchange	Biofuels from solid wastes	108,000	93,600	2010-10-01	2013-03-31
GAS BIOREF	249804	Collaborative project	Gasification of biofuels and recovered fuels	14,449,681	8,339,765	2010-12-01	2014-11-30
GASPRO-BIO-WASTE	261911	Research for SMEs	Universal gasification process analyser for biomass and organic waste treatment	1,500,695	1,157,024	2011-01-01	2012-12-31
DEMOCLOCK	268112	Collaborative project	Demonstration of a cost effective medium size Chemical Looping Combustion through packed beds using solid hydro-carbons as fuel for power production with CO_2 capture	8,193,828	5,304,509	2011-06-01	2015-05-31
INORGASS	251863	Marie Curie Intra-European Fellowships	Determination of the Fate of Inorganic Components upon Gasification of Sewage Sludge	229,747	229,747	2011-10-01	2013-09-30
PYROGAS	286244	MC Industry-Academia Partnerships	The integration of intermediate pyrolysis and vapour gasification to create and effective and efficient biomass-to-energy system for combined heat and power	1,082,575	1,082,575	2012-04-01	2016-03-31
PLAGASMIC	315604	Research for SMEs	Advanced Microwave Plasma Gasification of pig and cow manure for cost-effective biogas generation	1,482,071	1,135,000	2012-09-01	2014-08-31
UNIFHY	299732	JTI-FCH Collaborative Project	UNIQUE gasifier for hydrogen Production	3,438,061	2,203,599	2012-09-01	2015-12-31
ENV-BIO	318927	MC International research staff exchange scheme	Technical and environmental analysis of advanced strategies for the energy valorisation of biomass	302,400	302,400	2013-01-01	2016-12-31
PHENOLIVE	605357	Research for SMEs	Revalorization of wet olive pomace through polyphenol extraction and steam gasification	1,511,816	1,143,988	2013-10-01	2016-06-30
FlexiFuel-SOFC	641229	Research and Innovation action	Development of a new and highly efficient micro-scale CHP system based on fuel-flexible gasification and a SOFC	5,988,164	5,982,101	2015-05-01	2019-04-30
FlexiFuel-CHX	654446	Research and Innovation action	Development of a fuel flexible and highly efficient ultra low emission residential-scale boiler with coupled heat recuperation based on flue gas condensation	4,309,610	3,514,398	2016-01-01	2018-12-31
HiEff-BioPower	727330	Research and Innovation action	Development of a new highly efficient and fuel flexible CHP technology based on fixed-bed updraft biomass gasification and a SOFC	4,997,371	4,997,371	2016-10-01	2020-09-30
FLEDGED	727600	Research and Innovation action	FLExible Dimethyl ether production from biomass Gasification with sorption-enhancED processes	5,555,830	5,306,455	2016-11-01	2020-10-31
COMSYN	727476	Research and Innovation action	Compact Gasification and Synthesis process for Transport Fuels	5,096,660	5,096,660	2017-05-01	2021-04-30

Annex 8. Biomass algae projects

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
HARVEST	238017	Marie Curie Networks for Initial Training	Control of light use efficiency in plants and algae - from light to harvest	4,683,560	4,683,560	2009-10-01	2013-09-30
SUNBIOPATH	245070	SME focused research project	Towards a better sunlight to biomass conversion efficiency in microalgae	4,366,895	2,998,182	2010-01-01	2013-02-28
GIAVAP	266401	Large-scale integrating project	Genetic Improvement of Algae for Value Added Products	7,184,971	5,596,607	2011-01-01	2013-12-31
ALL-GAS	268208	Collaborative project	Industrial scale demonstration of sustainable algae cultures for biofuel production	11,773,672	7,106,680	2011-05-01	2016-04-30
BIOFAT	268211	Collaborative project	Biofuel from algae technologies	10,016,183	7,773,133	2011-05-01	2015-04-30
DOP-ECOS	293953	Marie Curie Career Integration Grants	Optimal Design and Operation of Microbial Ecosystems for Bioenergy Production and Waste Treatment	100,000	100,000	2011-09-01	2015-08-31
OPERATION SWAT	286840	Research for SMEs	High algal recovery using a Salsnes Water to Algae Treatment (SWAT) filter technology	1,345,061	1,060,477	2011-11-01	2013-10-31
SOLALGEN	286013	Research for SMEs	Hybrid algae cultivation system based on conditioned environment with efficient light collection and distribution system	1,483,818	1,136,008	2011-12-01	2013-12-31
ALGADISK	286887	Research for SMEs associations	Novel algae-based solution for CO_2 capture and biomass production	3,198,327	2,416,600	2012-01-01	2014-12-31
ALGAENET	295165	Marie Curie International Research Staff Exchange Scheme	Renewable energy production through microalgae cultivation: closing material cycles	709,800	709,800	2012-02-01	2016-01-31
AT~SEA	280860	Collaborative Project	Advanced textiles for open sea biomass cultivation	4,661,996	3,399,793	2012-04-01	2015-07-31
AlGEMAX	315298	Research for SMEs	Reduction of microalgae harvesting costs via the development of an ultrasound flow cell to provide pre-concentration	1,470,912	1,119,986	2012-10-01	2014-10-31
ALFF	642575	MC Innovative Training Networks	The Algal Microbiome: Friends and Foes	3,794,115	3,794,115	2015-01-01	2018-12-31
ECO-LOGIC GREEN FARM	683515	SME instrument Ph. 2	Design of an agricultural greenhouse for intensive growing of microalgae in fresh / sea water with a syngas production plant and organic farming of chickens and pigs outdoors	3,554,500	2,488,150	2015-08-01	2017-01-31
PHARM AD	661427	Marie Curie Individual Fellowships	Removal of pharmaceutical micro-pollutants from waste water by anaerobic digestion and its effect on nitrogen recovery from digestate by micro-algae.	183,455	183,455	2015-08-01	2017-07-31
ALGAE4A-B	691102	MC Research and Innovation Staff Exchange	Development of Microalgae-based novel high added-value products for the Cosmetic and Aquaculture industry	972,000	972,000	2016-01-01	2019-12-31
MacroFuels	654010	RIA - Research and Innovation action	Developing the next generation macro-algae based biofuels for transportation via advanced bio-refinery processes	5,999,893	5,999,893	2016-01-01	2019-12-31

Acronym	Project number	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
SOLENALGAE	679814	ERC-STG - Starting Grant	Improving photosynthetic solar energy conversion in microalgal cultures for the production of biofuels and high value products	1,441,875	1,441,875	2016-03-01	2021-02-28
BEAL	682580	ERC-COG - Consolidator Grant	Bioenergetics in microalgae: regulation modes of mitochondrial respiration, photosynthesis, and fermentative pathways, and their interactions in secondary algae	1,837,625	1,837,625	2016-06-01	2021-05-31
INDALG	733718	SME instrument Ph. 2	Development of an innovative algae based tertiary wastewater treatment and value recovery system	2,098,984	1,469,289	2016-10-01	2019-03-31
INTERCOME	733487	SME instrument Ph. 2	INTERnational COmmercialization of innovative products based on MicroalgaE	2,426,438	1,698,506	2016-12-01	2018-11-30
SABANA	727874	Innovation action	Sustainable Algae Biorefinery for Agriculture aNd Aquaculture	10,646,705	8,848,524	2016-12-01	2020-11-30
BIOMIC-FUEL	702911	Marie Curie Individual Fellowships	Bio-inspired photonics for enhanced microalgal photosynthesis in biofuels	251,858	251,858	2017-01-01	2019-12-31
GENIALG	727892	Innovation action	GENetic diversity exploitation for Innovative macro-ALGal biorefinery	12,224,238	10,885,817	2017-01-01	2020-12-31
VALUEMAG	745695	BBI Research and Innovation action	Valuable Products from Algae Using New Magnetic Cultivation and Extraction Techniques	4,789,000	4,789,000	2017-04-01	2020-03-31
ABACUS	745668	BBI Research and Innovation action	Algae for a biomass applied to the production of added value compounds	5,135,861	4,653,659	2017-05-01	2020-04-30
ALGAMATER	767333	SME instrument Ph. 2	Using microalgae bioreactor technology to deliver the world's most cost-effective, energy-efficient and adaptable system for the treatment of toxic industrial and landfill wastewater	2,906,000	2,034,200	2017-06-01	2019-05-31
BIOSEA	745622	BBI Research and Innovation action	Innovative cost-effective technology for maximizing aquatic biomass-based molecules for food, feed and cosmetic applications	4,491,383	2,611,223	2017-06-01	2020-05-31
MAGNIFICENT	745754	Bio-based Industries Research and Innovation action	Microalgae As a Green source for Nutritional Ingredients for Food/Feed and Ingredients for Cosmetics by cost-Effective New Technologies	5,886,579	5,330,573	2017-06-01	2021-05-31
CMHALGAE	751637	Marie Curie Individual Fellowships	Multifunctional Cellulose Magnetic Hybrid (CMH) Nanomaterial for Integrating Downstream Processing of Microalgae	160,800	160,800	2017-08-02	2019-08-01
MONSTAA	749910	Marie Curie Individual Fellowships	Metabolism of Novel Strains of Arctic Algae	231,642	231,642	2017-09-01	2020-04-30
ALGAECEUTICALS	778263	MC Research and Innovation Staff Exchange	Development of microalgae-based natural UV Sunscreens and Proteins as cosmeceuticals and nutraceuticals	1,129,500	1,129,500	2018-01-01	2021-12-31

Annex 9. Biomass biorefineries projects

Acronym	Project no.	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
PROPANERGY	212671	SME focused research project	Integrated bioconversion of glycerine into value-added products and biogas at pilot plant scale	2,748,295	1,823,893	2008-01-01	2011-12-31
GLYFINERY	213506	SME focused research project	Sustainable and integrated production of liquid biofuels, bio-energy & green chemicals from glycerol in biorefineries	4,973,221	3,754,806	2008-03-01	2012-02-29
BIOREF-INTEG	212831	CSA-SA - Support actions	Development of advanced biorefinery schemes to be integrated into existing industrial fuel producing complexes	1,452,930	995,082	2008-06-01	2010-05-31
SUSTOIL	213637	CSA-SA - Support actions	Developing advanced biorefinery schemes for integration into existing oil production/transesterification plants	1,178,874	992,197	2008-06-01	2010-05-31
AFORE	228589	Large-scale integrating project	Forest biorefineries: Added-value from chemicals and polymers by new integrated separation, fractionation and upgrading technologies	10,746,919	7,600,000	2009-09-01	2013-08-31
SUPRA-BIO	241640	Collaborative project	Sustainable products from economic processing of biomass in highly integrated biorefineries	17,460,612	12,318,163	2010-02-01	2014-07-31
BIOCORE	241566	Collaborative project	Biocommodity refinery	20,522,739	13,920,237	2010-03-01	2014-02-28
EUROBIOREF	241718	Collaborative project	European multilevel integrated biorefinery design for sustainable biomass processing	36,648,416	23,073,794	2010-03-01	2014-02-28
SYNPOL	311815	Collaborative Project	Biopolymers from syngas fermentation	9,939,222	7,344,554	2012-10-01	2016-09-30
SUBICAT	607044	Marie Curie Initial Training Networks	Sustainable biomass conversions by highly efficient catalytic processes	3,943,850	3,943,850	2013-10-01	2017-09-30
MIRACLES	613588	Collaborative Project	Multi-product integrated biorefinery of algae: from carbon dioxide and light energy to high-value specialties	11,911,245	8,991,903	2013-11-01	2017-10-31
D-FACTORY	613870	Collaborative Project	The microalgae biorefinery	10,083,864	7,177,440	2013-12-01	2017-11-30
VALOR-PLUS	613802	Collaborative Project	Valorisation of biorefinery by-products leading to closed loop systems with improved economic and environmental performance	9,950,805	7,413,755	2013-12-01	2017-11-30
INNPROBIO	652599	CSA - Coordination and support action	Forum for Bio-Based Innovation in Public Procurement	1,971,806	1,964,869	2015-03-01	2018-02-28
VALOWASTE	624609	Marie Curie Int. Incoming Fellowship	Valorisation of waste streams from the agro food sector	230,037	230,037	2015-06-01	2017-05-31
PULP2VALUE	669105	BBI Innovation action - Demo	Processing Underutilised Low value sugarbeet Pulp into VALUE added products (PULP2VALUE)	11,428,348	6,589,180	2015-07-01	2019-06-30
US4GREENCHE M	669055	BBI Research and Innovation action	Combined Ultrasonic and Enzyme treatment of Lignocellulosic Feedstock as Substrate for Sugar Based Biotechnological Applications	3,803,925	3,457,603	2015-07-01	2019-06-30
SUN-to-LIQUID	654408	Research and Innovation action	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	6,150,031	4,450,618	2016-01-01	2019-12-31
EXILVA	709746	BBI Innovation action - Flagship	Flagship demonstration of an integrated plant towards large scale supply and market assessment of MFC	44,698,677	27,433,611	2016-05-01	2019-04-30
BIOSKOH	709557	Bio-based Industries Innovation action - Flagship	BIOSKOH's Innovation Stepping Stones for a novel European Second Generation BioEconomy	30,122,314	21,568,194	2016-06-01	2021-05-31
BIOFOREVER	720710	BBI Innovation action-Demo	BIO-based products from FORestry via Economically Viable European Routes	16,212,634	9,937,997	2016-09-01	2019-08-31
STAR4BBI	720685	BBI Coordination	Standards and Regulations for the Bio-based Industry	995,878	995,878	2016-09-01	2019-08-31

Acronym	Project no.	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
		and Support action					
BIOMATES	727463	Research and Innovation action	Reliable Bio-based Refinery Intermediates	5,923,316	5,923,316	2016-10-01	2020-09-30
MACRO CASCADE	720755	BBI Research and Innovation action	MACRO CASCADE – Cascading Marine Macroalgal Biorefinery	4,455,064	4,156,356	2016-10-01	2020-09-30
EnzOx2	720297	BBI Research and Innovation action	New enzymatic oxidation/oxyfunctionalization technologies for added value bio-based products	5,000,000	3,000,000	2016-11-01	2019-10-31
FUNGUSCHAIN	720720	BBI Innovation action - Demo	Valorisation of mushroom agrowastes to obtain high value products	8,143,661	5,700,547	2016-11-01	2020-10-31
InDIRECT	720715	BBI Research and Innovation action	Direct and indirect biorefinery technologies for conversion of organic side-streams into multiple marketable products	2,089,671	1,347,948	2016-11-01	2019-10-31
Ambition	731263	Research and Innovation action	Advanced biofuel production with energy system integration	2,494,986	2,494,986	2016-12-01	2019-11-30
FALCON	720918	Research and Innovation action	Fuel and chemicals from lignin through enzymatic and chemical conversion	6,555,884	6,148,784	2017-01-01	2020-12-31
RES URBIS	730349	Research and Innovation action	REsources from URban BIo-waSte	3,377,915	2,996,689	2017-01-01	2019-12-31
TASAB	706642	Marie Curie Individual Fellowships	Towards a sustainable algal biorefinery	183,455	183,455	2017-01-01	2018-12-31
LIGNINFIRST	725762	ERC Consolidator Grant	The Lignin-First Approach for the Full Valorisation of Lignocellulosic Biomass	1,999,756	1,999,756	2017-03-01	2022-02-28
4REFINERY	727531	Research and Innovation action	Scenarios for integration of bio-liquids in existing REFINERY processes	5,965,474	5,965,474	2017-05-01	2021-04-30
LIGNOFLAG	709606	BBI Innovation action - Flagship	Commercial flagship plant for bioethanol production involving a bio-based value chain built on lignocellulosic feedstock	34,969,215	24,738,840	2017-06-01	2022-05-31
URBIOFIN	745785	BBI Innovation action - Demo	Demonstration of an integrated innovative biorefinery for the transformation of Municipal Solid Waste (MSW) into new BioBased products (URBIOFIN)	15,061,283	10,946,366	2017-06-01	2021-05-31
PEFERENCE	744409	BBI Innovation action - Flagship	From bio-based feedstocks via di-acids to multiple advanced bio-based materials with a preference for polyethylene furanoate	44,818,923	24,999,610	2017-09-01	2022-08-31
SSUCHY	744349	BBI Research and Innovation action	Sustainable structural and multifunctional biocomposites from hybrid natural fibres and bio-based polymers	7,411,151	4,457,195	2017-09-01	2021-08-31
SYLFEED	745591	BBI Innovation action - Demonstration	From forest to feed: enable the wood industry to bridge the protein gap	15,579,451	10,892,599	2017-09-01	2021-08-31
AGRICHEMWHEY	744310	BBI Innovation action - Flagship	An integrated biorefinery for the conversion of dairy side streams to high value bio-based chemicals	29,949,323	22,007,931	2018-01-01	2021-12-31
BioCatPolymers	760802	Innovation action	Sustainable and efficient bio-chemical catalytic cascade conversion of residual biomass to high quality biopolymers	5,351,985	4,362,048	2018-01-01	2020-12-31
BioRECO2VER	760431	Research and Innovation action	Biological routes for CO_2 conversion into chemical building blocks	6,990,938	6,812,188	2018-01-01	2021-12-31
ENGICOIN	760994	Research and Innovation action	Engineered microbial factories for CO_2 exploitation in an integrated waste treatment platform	6,986,910	6,986,910	2018-01-01	2021-12-31
IProPBio	778168	MC Research and	Integrated Process and Product Design for Sustainable	684,000	594,000	2018-01-01	2021-12-31

Acronym	Project no.	Funding scheme	Project name	Overall Budget	EU Funding	Start	End
		Innovation Staff Exchange	Biorefineries				

KJ-BK-19-004-EN-N

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Publications Office of the European Union

doi:10.2760/919071

ISBN 978-92-76-12432-0