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LOW CARBON ENERGY OBSERVATORY

HEAT AND POWER FROM BIOMASS

Technology development report

Joint Research Centre

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Explanatory Foreword on the Low Carbon Energy Observatory

The LCEO is an Administrative Arrangement being executed by DG-JRC for DG-RTD, 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

In addition, the LCEO monitors future emerging concepts relevant to these technologies.

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 deliverables?

The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Report on Synergies for Clean Energy Technologies
- Annual Report on Future and Emerging Technologies (information is also systematically updated and disseminated on the online FET Database).

Techno-economic modelling results are also made available via dedicated review reports of global energy scenarios and of EU deployment scenarios.

What's the timeline?

The LCEO produces its main reports on a two-year cycle. The first set was published in 2016 and the second was available in 2018. The present report is the last in this series to be released in spring 2020.

How to access the deliverables

Commission staff can access all reports on the Connected LCEO page. These are restricted to internal distribution as they may contain confidential information and/or assessments intended for in-house use only. Redacted versions will also be distributed publicly on the SETIS website.

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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. The RES II includes 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. In addition, biofuels and bioenergy from forest materials must comply with requirements which mirror the principles contained in the EU Land Use, Land Use Change and Forestry (LULUCF) Regulation. 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 European Commission presented the 'European Green Deal' in December 2019 to make EU a climate-neutral economy by 2050 (COM(2019) 640). In order to move to a clean, circular economy and stop climate change, the EU Green Deal provides a roadmap with actions to boost the efficient use of resources. Bioenergy, as part of a circular bioeconomy, could have an essential contribution to reach climate neutrality by 2050, enabling higher shares of renewables in the energy grids through high efficiency heat and power generation and enabling negative emissions through carbon capture, utilisation and storage. Besides contributing to greenhouse gas reduction, bioenergy brings additional social, environmental and economic benefits to agriculture, forestry and other industrial sectors, driving rural development, in the context of sustainable development.

The global primary energy supply from biomass has reached about 56 EJ in 2018, 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 9% of the global final energy consumption (IEA 2020). 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 2018 of about 118 GW at worldwide level and 35 GW in operation in the EU, world leader for bio-power generation and capacity. The global biomass electricity power generation also reached 596 GWh in 2018, with a large share of biomass electricity being produced in the EU (188 TWh). Global biogas production increased from 0.28 EJ in 2000 to 1.33 EJ in 2017, with a global volume of 36 billion m^3 methane equivalent, of which 18 billion m^3 methane equivalent being produced in the European Union (Eurostat 2018, IEA 2020). The global installed biogas capacity reached in 18 GW in 2018, with more than 12.5 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 88 TWh in 2018 (Eurostat 2020, Irena 2020).

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 2018, 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 80% of modern renewable heat generation in 2015 (IEA 2020, Eurostat 2020). 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 704 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.

This Heat and Power from Biomass Technology Development Report 2020 includes updates on the technology state of the art and development trends. The impact assessment of projects is focused on H2020 projects and reports on the status of the most relevant on-going projects in each sub-technology. The modelling results include a new scenario (the SET plan scenario) which provides a new foresight perspective into the expected developments. Trends, barriers and conclusions presented in the 2018 report remain still valid at the time of publishing this report.

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, anaerobic digestion, 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 forecast was based on the JRC-EU-TIMES model to estimate the future contribution of bioenergy production in the European energy sector (Nijs et al., 2018).

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).

By searching for a combination of keywords[1] in the Community Research and Development Information Service (CORDIS), for each selected sub-technology we identified the relevant projects, funded under the Horizon 2020 programme (H2020) and carried out further analysis, in terms of objectives and main achievements in order to provide general considerations on their impact on the development of the technology. 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 the COMPASS tool where relevant documents on the selected projects (including the project proposal and deliverables) were made available by DG RTD (Cordis 2020).

[1] The used keywords are: bioenergy, anaerobic digestion, biogas, biomass combustion, gasification, syngas, pyrolysis, thermochemical conversion, biomethane, hydrothermal processing, hydrothermal liquefaction, hydrothermal carbonisation, algae, biorefinery.

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, other databases and project websites. The main focus has been on the assessment of project results from EU-funded H2020 (2014-2020) RTD programme, 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. An important source of information was COMPASS, the monitoring tool for research projects operated by Directorate-General for Research and Innovation (DG RTD).

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 resources 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 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 (10-50 MW) 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.

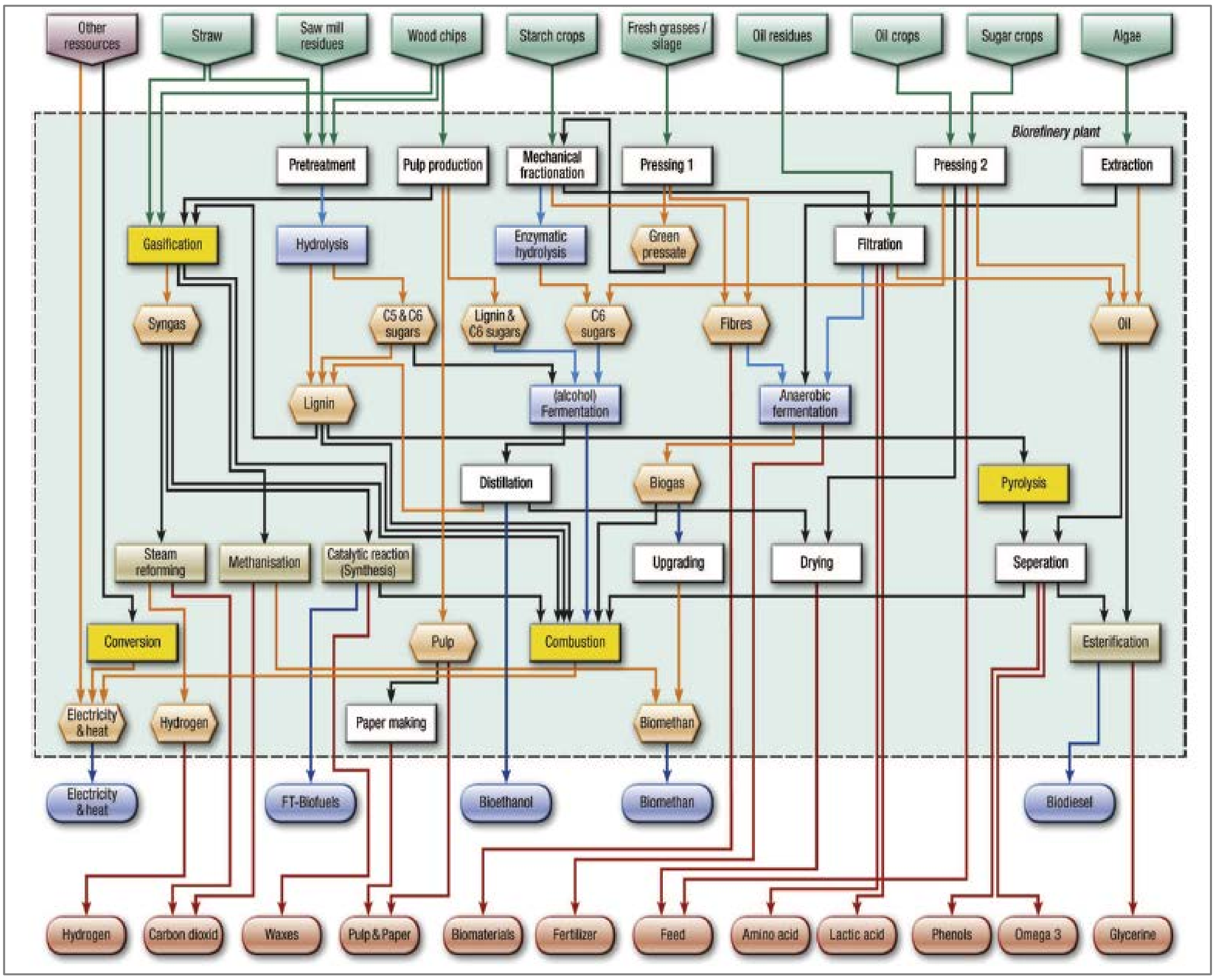
Biorefineries integrate production of **high-value, low-volume and low-value, high-volume products** that are produced in a variety of processes designed to maximize / optimize the use of resources and minimize the waste streams. The high-value products enhance the cost efficiency of the whole refinery, 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 4 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 1 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.

2.6 Patenting trends

For the assessment of the technical progress achieved in the field of biomass technologies for heat and power, we performed an analysis of the trend in the total number as well as the world distribution of patent filings for the time period between 2000 and 2016 as extracted from PATSTAT database (JRC based on data from the European Patent Office - EPO, 2019; Pasimeni, 2019; Pasimeni et al., 2019). In order to estimate the share in total inventions a fractional count should be adopted, where inventions tagged with more than one code contribute with an equal fraction to all the codes (classes) involved. Additional information on the methodology used to compile the patent statistics is available in Fiorini et al., 2017; Pasimeni, 2019 and Pasimeni et al., 2019.

Patents related to biomass for heat and power sector are identified by using the relevant code families of the Cooperative Patent Classification (CPC), for the technologies or applications for mitigation or adaptation against climate change, reduction of greenhouse gases emission related to energy generation, transmission or distribution. The Y codes are designed to facilitate the identification of inventions relevant to renewable energy and climate mitigation technologies. Within this classification, the set of technical classes of inventions that can be related to the biomass technologies, are patent families with code Y02E related to energy generation, transmission or distribution and the Y02E 50 code that include CPC classes referred as 'technologies for the production of fuel of non-fossil origin'.

From this broad category, we selected the sub-categories referring to 'biofuels' identifying the technologies that are relevant for this technology report, such as bio-pyrolysis, torrefaction of biomass, CHP turbines for biofeed and Gas turbines for biofeed. We also selected the sub-categories referring to and 'biomass as fuel' and 'fuel from waste' and 'methane' that are relevant for this technology report. It should be noted that the selected CPC classes are quite broad and may still include a range of biomass-based process technologies that relate to the biomass for heat and power but also to biofuels that use the same technologies for production (anaerobic digestion, pyrolysis, gasification, etc.).

The classes that are included in the present analysis often refer to “biofuels”, but this does not mean biofuels for transport but in fact fuels from biomass, as bioenergy carriers. This could be overlapping with the biofuels for transport, but there is no possibility to differentiate between the final use of these products, as prolysis products or methane from anaerobic digestion can have various uses in transport or heat and power production.

The relevant patents are grouped under the following classes of patents:

Y02P Biomass or waste as fuel

Y02P 20/136 - of biological origin, e.g. biomass, biofuels, biogas

Y02P 40/126 - Waste

Y02P 40/128 - Biomass

Y02P 80/21 - Biomass as fuel

Y02E Biofuels

Y02E 50/11 - CHP turbines for biofeed

Y02E 50/12 - Gas turbines for biofeed

Y02E 50/14 - Bio-pyrolysis

Y02E 50/15 - Torrefaction of biomass

Y02E 50/34 - Methane (not used, see subgroups)

Y02E 50/343 - production by fermentation of organic by-products

Y02E 50/346 - from landfill gas

Figure 2 shows the trends for patents for biomass for heat and power technologies, according to the classes selected, at global level between 2000 and 2016 by year. The world patenting activity in ‘biofuel’ and ‘fuels from waste’ used for the production of energy carriers and heat and power generation registered a very significant increase from 2004 to 2016, showing a significant decline from 2010.

Figure 2 Trend of inventions in the world for biomass technologies

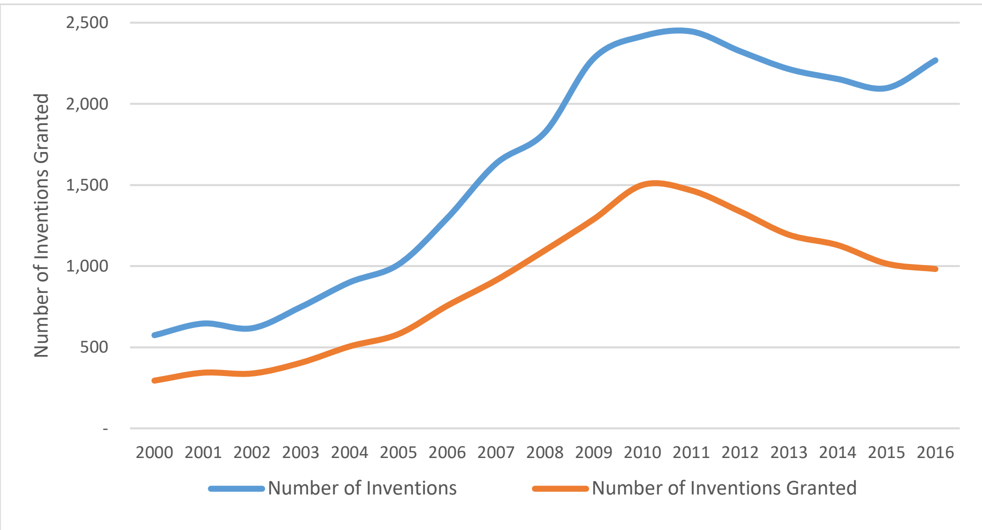


Figure 3 shows the number of granted inventions financed by the public or private sector during 2000-2016 in the world and in the EU. Private funding is steadily higher than public funding in the considered time period. World inventions financed by private funding reached the maximum number in 2011 followed by a decline, while the public inventions had a more continuous increase. In the EU, the peak in the number of inventions was reached in 2009 for the private funding, while the public inventions reached a peak in 2011, followed by a slow decline. This peak and the general trend could be explained by a number of factors, including the economic crisis, controversy about the sustainability aspects of biofuels and bioenergy and the rather negative public perception on the use of biomass for bioenergy and biofuel production.

Figure 3 Trend of inventions in the world for biomass technologies financed by public or private sector

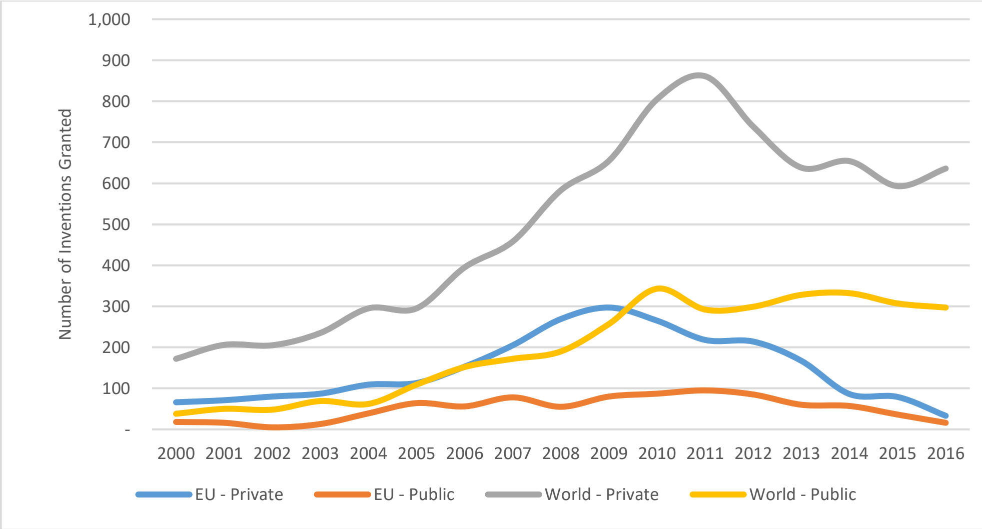


Figure 4 shows the trend of granted inventions financed by the public or private sector in the major world regions in the field of bioenergy technologies. The leading region on the number of inventions filled in the last years is by far China that showed a very large increase in the numbers of inventions granted every year. A similar trend was registered in Korea. Other world regions registered an increasing trend until 2009-2012, following a large decrease after this period, in particular in the European Union. Looking at the cumulative number of patents filled between 2000 and 2016 China is the leading country followed by Korea, the EU, Japan and the US.

Figure 4. Trend of inventions in the world for biomass technologies in major world regions

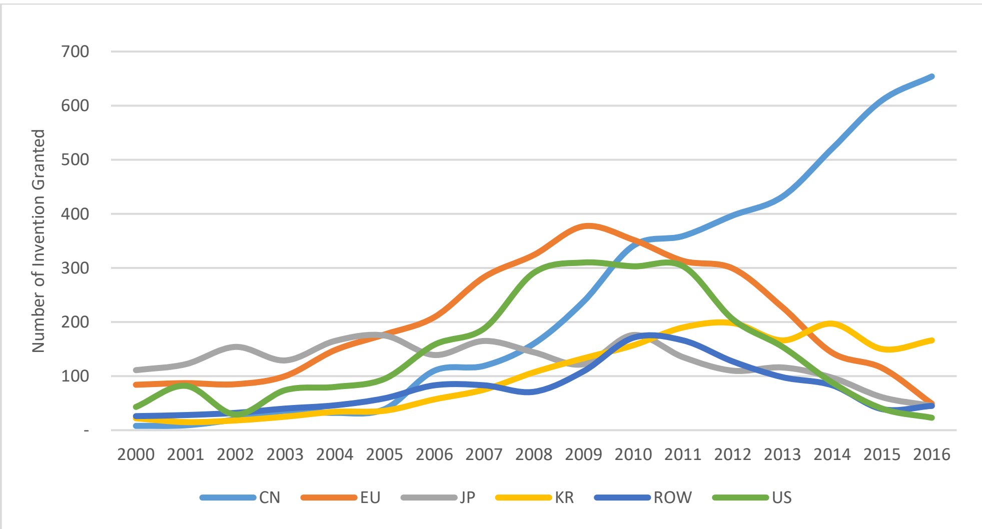


Figure 5 shows the trends in the annual number of inventions made for biomass for heat and power technologies according to CPC classes for biomass for heat and power between 2000 and 2016. A significant large number of patents and a large increase have been noticed for biofuels and biofuels from waste for various uses (not described) followed by methane production by fermentation of organic by-products or from landfill gas which show a large interest in developing biomethane technologies. Another large share of patents concerns the use of biomass as energy input and bio-pyrolysis.

Figure 5. Trend of granted inventions for different biomass CPC classes

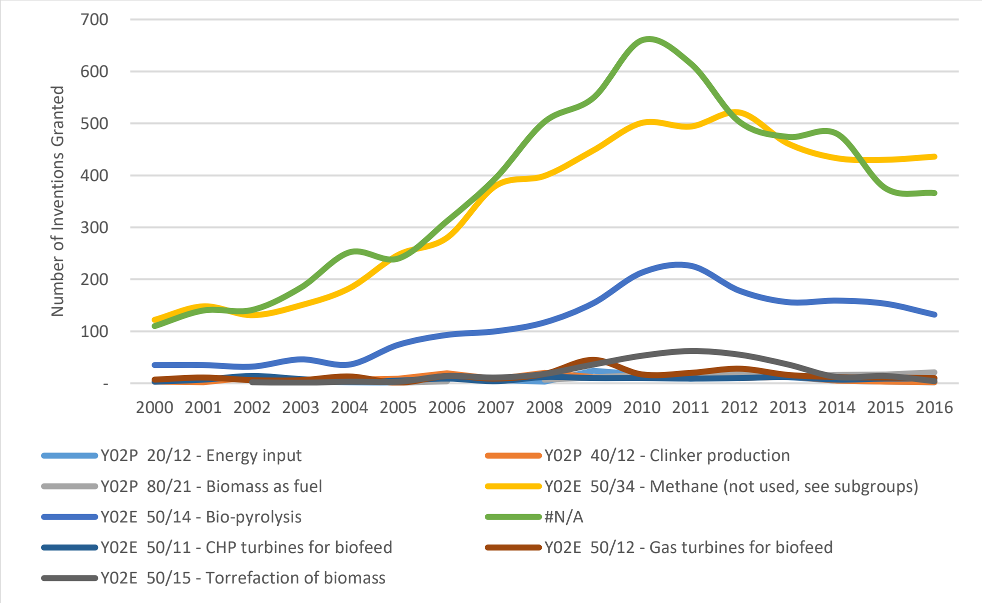


Figure 6 presents the shares of CPC sub-classes over the total granted inventions over the entire period (2000-2016). This shows that, among all sub-classes, the highest number of granted inventions was found for biofuels for various uses, followed by the methane production by fermentation of organic by-products from landfill gas, followed by bypolysis.

Figure 6. Shares of CPC sub-classes over the total granted inventions (2000-2016)

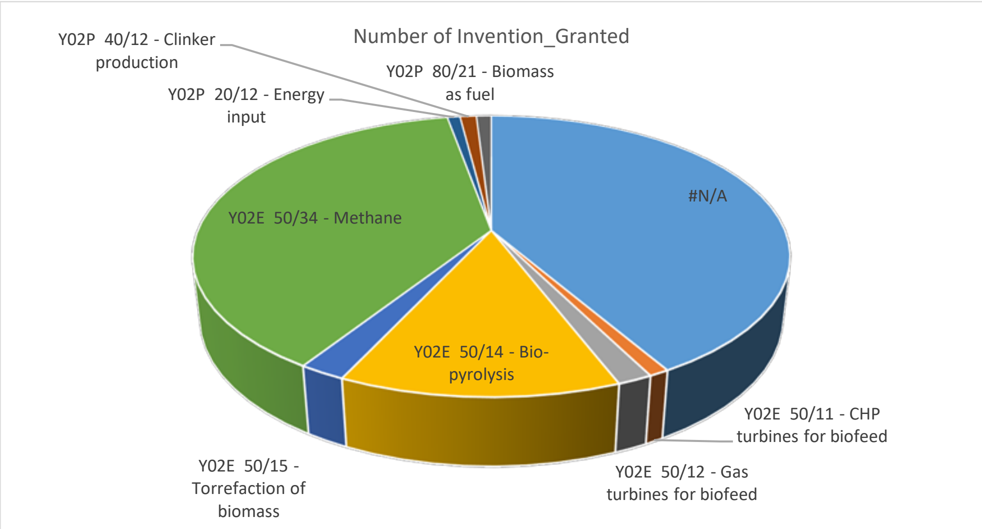
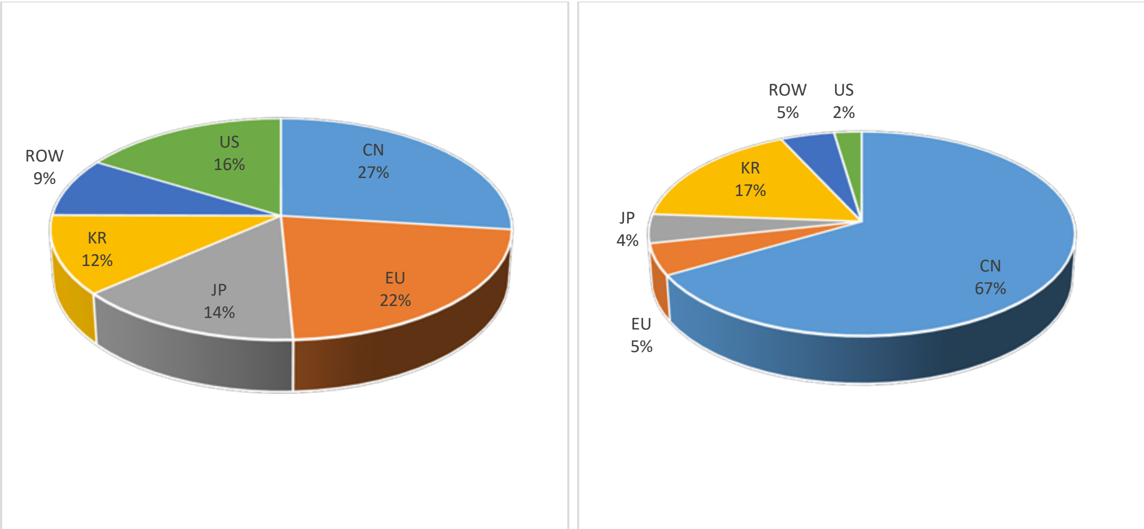


Figure **7** shows the share of granted invention activities in biomass by world players in 2000-2016 (left) and in 2016 (right). China is the country with the highest number of inventions over the entire period, with a share of 27% of granted inventions in the considered time period, followed by the European Union (22%), Japan (14%), US (16%) and Korea (11%). In 2016, the share of China share is much larger (67%), followed by Korea (17%), the Europen Union (5%) and US (2s%).

Figure 7 Share of granted invention activities in biomass by world player in 2000-2016 (left) and in 2016 (right)



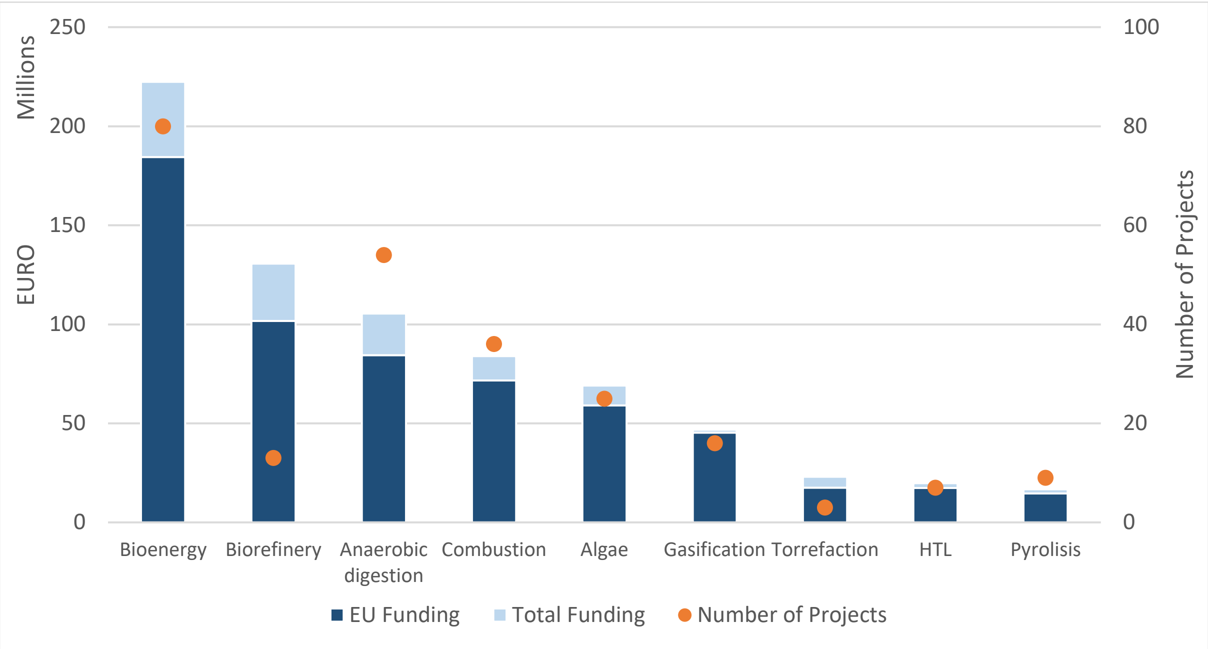
3 R&D Overview

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) The info on H2020 projects was collected from CORDIS database (European Commission Community Research and Development Information Service) and from the COMPASS tool for H2020 projects. 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 8. EU funding for bioenergy technologies and number of projects



The analysis of the EU funded projects revealed that a number of 244 projects on biomass for heat and power relating to technology development have been identified, totalling €718 m and receiving €596 m funding from the EU, addressing general bioenergy issues under the H2020 RTD EU programmes (Cordis 2020).

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 8. Significant funding has been provided for bioenergy, biorefinery projects, anaerobic digestion, combustion, algae and gasification. Pyrolysis, hydrothermal processing and torrefaction have received less funding. 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 anaerobic digestion 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 anaerobic digestion, fewer projects but with higher value addressed biorefineries.

Figure 9. Share of technology-related bioenergy projects
in terms of EU funds received (left) and number of projects (right)

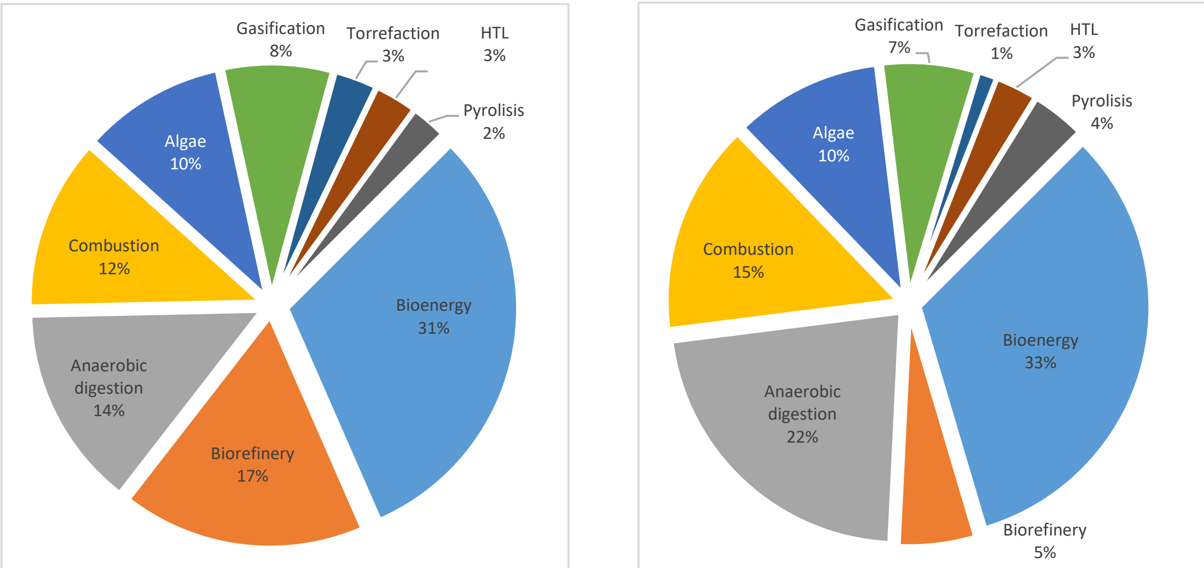


Figure 10. Total of the EU funding of the H2020 Programme grouped by country

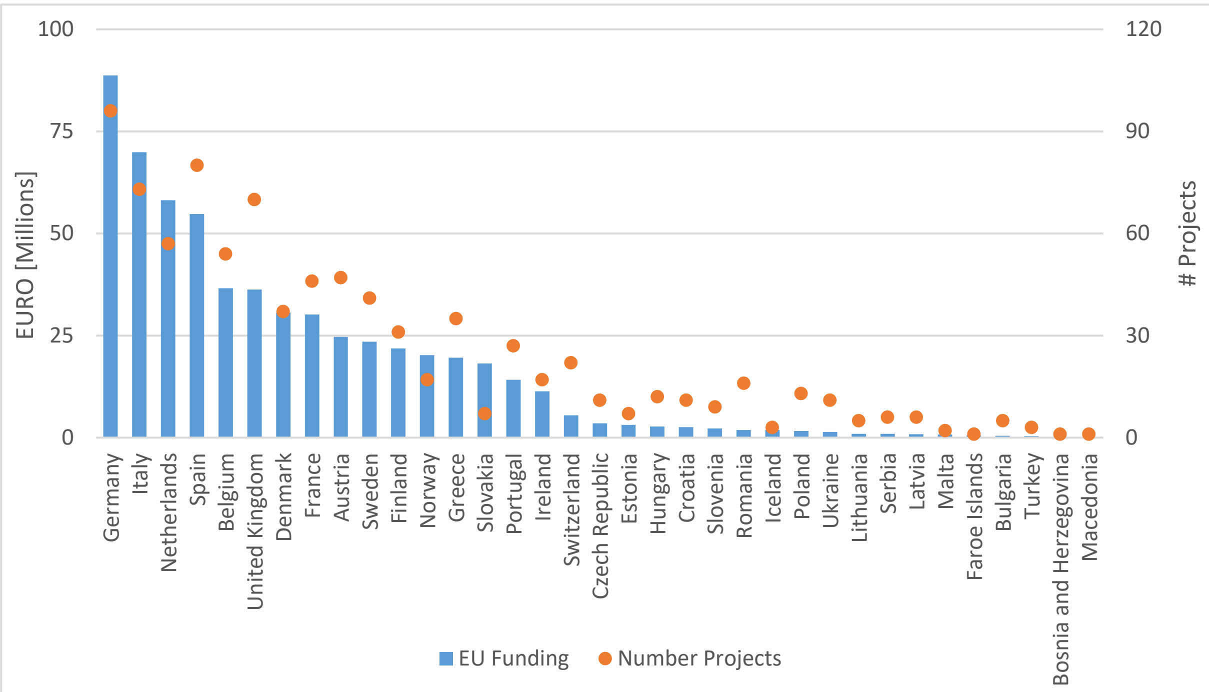


Figure 9 displays the share of various bioenergy projects in terms of the EU funds received and number of projects awarded. It is possible to observe that bioenergy biorefinery, and AD projects respond to around 60% of all EU funded projects. The biorefinery projects received almost 17% of the EU funds, although the number of projects reaches only 5% of the total. Bioenergy projects are in higher proportion (31% of the total) and they received just less than 33% of all EU funds. The anaerobic digestion projects correspond to about 22% of the projects and 14% of the total EU funds.

In general, the projects are executed by multiple institutions located in different countries. Figure 10 shows the distribution of the total EU funding related to the H2020 Programme grouped by country. Germany is the leading country in terms of received funding (15% of the total), followed by the Italy (12%), Netherlands (10%), Spain (9%) Belgium (6%) and United Kingdom (6%). The remaining European countries received altogether around 42% of the total EU funding. Important to note is that Germany was part of 40% of the EU projects, Italy was part of 30% of the projects, The Netherlands was part of 24% of the projects, Spain was part of 33% of the projects, Belgium was part of 22% of the projects and the UK was part of 29% of the EU projects.

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 to strengthen the European Research Area (**FACCE SURPLUS**) and to develop a long-term joint European Community Research and Innovation Agenda (ECRIA) on the integration of biofuels production and surplus electricity valorisation (**Ambition**). Some projects aimed to contribute to the SET-Plan activities and to the Strategic R&I Implementation Plan on Bioenergy and Renewable fuels (**ETIP Bioenergy-SABS, ETIP Bioenergy-SABS 2**). Some projects aimed to encourage and facilitate cooperative research in biomass across Europe coordinate, complement and update the information of the major European research infrastructures (**ERIFORE**). **BESTF3 ERA-NET** brings together a number of national and transnational organisations for promoting greater use of bioenergy to implement a joint programme for bioenergy demonstration projects to demonstrate enhanced bioenergy technologies.

European cooperation is fostered to address knowledge gaps, to promote to best practices and through training collaboration across the whole bioenergy value chain (**BioEnergyTrain**) on agri-sector (**AgRefine**) and to transfer of know-how and information for farmers and foresters (**AGRIFORVALOR**) to facilitate business model development for new bio-industry start-ups. A project (**GreenCarbon)** addressed research and training programmes for early-stage researchers to develop new scientific knowledge, capability, technology, and commercial products for biomass - derived carbon materials from pyrolysis and HTC.

Several projects addressed the issue of biomass potential mapping, through for example a low cost unmanned aerial platform and service (**COREGAL**), or new methods for an improved assessment of vegetation resources using satellite observations (**AfriVeg**). The issue of the need to have access to harmonised and timely forest information was addressed (**DIABOLO**) to enable the analysis of sustainable biomass supply derived from national forest inventories and facilitate near real-time forest disturbance monitoring, to ensure (**EFFORTE**) efficiency and sustainability of forestry, and to facilitate the implementation of better forest management models (**ALTERFOR**) to secure the capacity of the forests to provide balanced ecosystem services. Also, other projects addresses the potential of biomass from agrarian pruning and plantation removal (**uP_running**), the use of woody and herbaceous biomass from nature conservation and landscape management for energy production (**greenGain**) and innovative cropping systems that allow to protect and increase SOC stocks while increasing biomass production (**InBPSOC**).

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 (**SecureChain**). Several projects focused identifying, evaluating, initiating and upscaling bio-energy chains (**GRACE**), promoting efficient biomass value chains through the use of best practices in the provision of biomass (**ENABLING**) and achieve new value chains on agrifulture and forestry (**AGRIFORVALOR)**, or improving biomass supply chains through integration of ICT tools (ICT-BIOCHAIN).

The issue of logistics was addressed in several projects through the implementation of biomass logistic centres in the agro-industry 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. Digital Innovation Hubs (DIH) are being developed for increasing biomass mobilisation and improving biomass supply chains through integration of ICT tools (**ICT-BIOCHAIN)**. The development regional bioenergy concepts was addressed to develop the so-called bioenergy villages (**BioVill**) and the so-called Smart Renewable Hubs (**GRIDSOL**), integrating solar energy (CSP and PV) and biogas to ensure operation and grid stability with higher RES penetration through advanced control systems.

The issue of mobilising biomass was addressed in several prjects that developed harvesting machines for wood, agro waste and herbaceous biomass producing a tradable biomass format (briquette) (**CARGOMIL**), fast-growing trees (**BilletPro**), for harvesting and processing small diameter trees (**EcoBioMass**) and for biomass harvesting and pelleting in one single machine (**HarvPell**). A number of projects developed pelletising machines for agricultural residues (**AgroPellet, BioPellets**, **PELLETON**) some being mobile pelletizing units for manufacturing pellets from biomass and agricultural wastes (**Proxipel, PELLETON**). Several projects aimed to develop mobile, small-scale systems for on-site treatment of spatially scattered raw material sources for thermal conversion through hydrothermal pre-treatment, hydrothermal carbonisation and torrefaction and slow pyrolysis (**MOBILE FLIP**), gasification (**ENERCOVERY**), and for off-grid applications (**Enerbox**).

Some projects addressed biomass quality management that enables an intelligent biomass quality management across the whole supply chain (**ROBIOT**), fully-automated solutions, which provides reliable real-time data on biofuel quality (**OPTIFUEL**) and a novel biomass scanner for measurement of various types of biomass for quality determination of biofuels in real time (**BioValue**).

Several projects aimed at increasing the production, mobilisation and utilisation of biomass (**greenGain, uP_running**), including through the exploitation of biomass from marginal lands or underutilised lands (contaminated, abandoned, fallow land) (**FORBIO, SEEMLA**) and to uptake bioenergy projects on marginal, underutilized and contaminated lands (**BIOPLAT-EU**). The projects thus looked at breeding and cropping research (**LIBBIO**) in marginal lands conditions, development of industrial crops on marginal lands (**MAGIC**) or to demonstrate the upscaling of crop production of miscanthus and hemp on marginal, contaminated and unused land (the (**GRACE**).

Several projects have been carried out to promote the market uptake of bioenergy (**SecureChain**) and improve market uptake of intermediate bioenergy carriers (**MUSIC**) and to promote a Sustainable Supply Chain Management (SSCM) practice, to develop integrated solutions to promote the sustainable market for solid biofuels for residential heating (**Biomasud Plus**) and to support and promote the substitution of fossil fuels (**Bioenergy4Business**) by bioenergy sources (industrial waste, forest biomass, straw and other agri-biomass). A project (**REGATRACE**) to set up a trade system based on issuing and trading biomethane/renewable gases Guarantees of Origin (GoO) to promote biogas/biomethane. Some projects also addressed the support of European biogas/biomethane industry (**DiBiCoo**) to increase the production and use of biomethane, for grid injection and as transport fuel (**BIOSURF**)

Other projects focussed on the promotion of best practices and business models for renewable electricity generation (**BestRES, ENABLING**), to establish (both technical and non-technical) success factors for the development (**BIOFIT**) and the new business models (**Bioenergy4Business,**). Few projects aimed at developing of platforms of stakeholders to address societal, environmental and economic challenges related to biomass (**BIOREG**) and for better communication on the various bio-based products and applications and their benefits. Several projects aimed to remove non-technological barriers, such as low public acceptance, (**ISAAC**), introducing social innovation and engaging stakeholders at regional/local level for promoting, community energy initiatives (**ISABEL**) addressed communication and capacity building process with policy makers and other stakeholders (**progRESsHEAT**).

Various projects aimed to develop bioenergy hybrids, such as solar thermal /biomass hybrid air conditioning system for space cooling and heating of residential and commercial buildings (**Hybrid – BioVGE, SolBio-Rev**). Projects also addressed the development of a decentralized (on or off grid) H2PS-5 micro-CHP system to convert the fuel (LPG/NG/Biogas) into electrical and thermal power through a PEM fuel cell, with intermediate production of H2 (**Prometheus-5**) and innovative Power to Gas storage concepts (**STORE&GO**).

Some projects aimed to treating low-value biomass to remove the ash content and provide high quality feedstocks (**BIAR**) and to improve wood wastes valorisation (from construction, demolition and renovation works, furniture, packaging and civil engineering) (**BIOREG**). Several other projects proposed to provide new approaches for the valorisation of agricultural waste, including wastes from several agriculture (wine, olive oil, horticulture, fruit, grassland, swine, dairy and poultry and pig manure) (**NoAW**, **AgroCycle**, **DEPURGAN**). Several projects focussed to promote new treatment process for the wet biomass waste streams, biomass residues from agriculture or landscaping (**Res2Pel**), urban wastewater (**iMETland**), and developing new solution for the valorisation of waste from the food processing industry (**DRALOD**), as well as for the use of low-heat resources (**MOVARC**).

Several projects aimed to develop smart grids through cloud-based algorithm-driven hardware and monitoring and controlling gas pressure, flow & gas quality (**SmartGasGrid**), and also district heating systems as the most effective solution in densely populated areas (**KeepWarm**), intelligent district heating and cooling networks that integrate multiple sources (including high- and low-temperature solar thermal, biomass, PV, cogeneration and waste heat) (**FLEXYNETS**).

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 m 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 11th Joint Call for Research and Development Proposals of the ERA-NET Bioenergy and 1st 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 addressing technical and non-technical barriers for further development (**BiogasAction, BIOSURF, ISABEL, Record Biomap**). Several projects addressed biogas production and biogas upgrading, based on biological processes (**UBI**), catalyst or zeolite membrane separation (ZeoBio-NG), and for supplying local fuelling stations (**Bin2Grid**). Several projects aimed at biogas reforming and methanation to biomethane (Biogas2Syngas, CoMeth).

Various projects investigated the improvement options for biogas production to optimise the bio-methanisation and to increase the biogas yield through enzymes of bio-waste in order to produce energy for decreasing the energy cost (**DEMETER, FimusKraft**) and for reducing energy consumption and maximising biogas production to optimize the digester performance **OptiMADMix**). Several projects addressed promising innovative process and technology solutions from substrate pre-treatment, digestion, gas conditioning and digestate utilisation (**Record Biomap**), using multi-chamber reactors (**GASFARM**), multi- step bio-fermentation process **(FimusKraft**) or multi-phase anaerobic digester monitoring and decision support systems (**INCOVER**).

Several projects aimed to develop small-scale, modular compact biogas plants (**BIOGASTIGER**, **Biofrigas**), household biogas system converting organic waste into biogas (HOMEBIOGAS) or operates off-grid (**KUDURA**). Other projects focussed on modular wastewater treatment system that integrates anaerobic, aerobic and advanced oxidation stages (**ANAERGY**).

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 (**VegWaMus CirCrop**). While most projects focussed on the development and improvement of mesophilic anaerobic digesters (**OptiMADMix**), few projects addressed thermophilic and low-temperature anaerobic digestion (**Lt-AD**).

Some projects focussed on the use of anaerobic digestion of all types of biomass including lignocellulosic biomass suchcrop residues (straw) (**DualMetha**). Some projects also addressed the biogas production from lignocellulosic wastes through high-temperature and high-pressure (BioFuel Fab) or biological (**BIORELOAD**) pre-treatment processes or a microwave pre-treatment technique (**Biowave**) that increases the compatibility of feedstocks for anaerobic digestion. Different projects addressed the anaerobic digestion of various residues, including food waste, biowaste or slaughterhouse waste (**BPV, DECISIVE, SYSTEMIC, Lt-AD, VegWaMus CirCrop)**.

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**). 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 (**AMBIENCE**).

Many projects addressed the AD of various biomass streams to produce biogas for electricity and heat (**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 CHP systems or fuel cells (**Prometheus-5, DEMOSOFC**) with the production of hydrogen (**BIONICO, BioROBURplus, H2AD**). 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, to obtain liquid fertilizers with high organic matter content, for transforming the digestion effluents into bio-fertilisers. Some projects focussed to develop processes for converting biodegradable fractions of various biowaste and residues into high value-added products, biogas and organic based fertilizer (**BIOFERLUDAN, Record Biomap, KATEDRAL, SYSTEMIC**).

Several projects addressed the issue of carbon extraction and nitrogen nitrogen-control technology for nitrogen and phosphorus recovery (**ADD-ON, AnBIOSST, BIOFERLUDAN, MUBIC, NOMAD**) for bio-fertilisers and nutrient-balanced soil conditioners and for biomaterials and valuable platform chemicals (**BioRECO2VER, BIOGRAPHENE, ENGICOIN**). Several projects addressed processes for waste management of sewage sludge (AnBIOSST, BioROBURplus, SHEPHERD), turning it into valuable by-products and energy such as biogas, clean water and natural fertilizers (KATEDRAL). A project addressed the removal of micropollutants or pharmaceutical residues from sludge and wastewaters (**PHARM AD**) in novel application of anaerobic digestion to the direct treatment of wastewaters.

Biogas innovative concepts and approaches for wastewater treatment plants were investigated (**POWERSTEP**). Some projects aimed to demonstrate innovative concepts and design schemes of wastewater treatment (**FlexBio, PHARM AD, VicInAqua**) for heat ant power production (**DEMOSOFC, POWERSTEP**) based on a combination of anaerobic technology and aerobic membrane bioreactors (**FlexBio**).

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 smart 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 m 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 m) 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 (CHF 25 million 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 (**HYBURN, 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 (**VADEMECOM**) by means of experimental, theoretical, and numerical simulation approaches. Research focussed to run combustion simulations to design efficient furnaces, engines, etc. (**HPC4E**) to analyse and model turbulent combustion phenomena (**MILESTONE, HYBURN**), to model biomass combustion fenomena (**DT4BIOMASS**).

A number of projects aimed to develop new biomass combustion systems based on new concepts including intelligent devices for wood stoves automating and optimizing combustion (**FLORIAN**) and smart pellet stoves that integrates smart home appliances that allows remote monitoring, New concepts and new biomass furnaces were developed for the conversion of biomass into energy with lower investment, lower operational costs and lower emissions (**DEBS**), smart steam boilers (EcoVapor), condensing biomass boilers (**C-HEAT**), efficiency improved boilers lower bioenergy CAPEX and OPEX (**BELENUS**). Some projects addressed the need to increasing the efficiency of CHP plants by elevated steam parameters (**Biofficiency**) and converting an ultra-supercritical coal-fired power plant into a biomass-fired by repowering with thermally-treated biomass (**ARBAHEAT**) (torrefaction, hydrothermal carbonization and steam explosion).

Some projects aimed to develop multifuel and fuel-flexible burner that can use different types of biomass available (**BioBur**, **BIOBURNER**) and fuel flexible full-scale hybrid plant concept using for gaseous sustainable biomass feedstock such as biogas, fuels, hydrogen or (lean) biogas mixtures, landfill gas or (pyrolysis) process gases (**Bio-HyPP, HyBurn**).

Some projects focused their work to study of the combustion behaviour of biomass fuels, of the ash fusion behaviour. The issue of biomass and ash composition was addressed in several projects, investigating the melting ash behaviour that causes slagging and fouling of furnaces (**Biofficiency, POWERICE**) and preventing or mitigating corrosion (**BELENUS**). Several projects addressed the issue of extracting valuable materials from the remainder ash, such as phosphorus (**RECaPhos, SINTRAN**).

Several projects addressed the issues of the pollutant and particulate emissions to make breakthroughs in our understanding of particles from biomass burning and their impacts (**PyroTRACH**) and to develop solutions for biomass combustion, achieving gaseous and particulate matter reduction (**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 devices that reduce gas and particle emissions (**FLORIAN**) and concepts to achieve low gaseous and particulate emissions at small scale (**cleanFIRE**, **DEBS, EcoVapor, INSERTRONIC**).

Several projects focused to develop and demonstrate various concepts and approaches for energy recovery from various waste materials and other biomass feedstock (**SINTRAN**) and residues from agriculture (such as rice straw) and agrobiomass (**AgroBioHeat, POWERICE**). Several projects focussed to demonstrate cost-effective and high efficiency large scale energy generation systems using low and medium-temperature (from below 120 ºC to 150-400 ºC) to recover the low-grade waste heat and transform it into heat and power. Some projects aimed to develop small scale (1 to 50 kWe) (**DeReco, Exergyn Drive, IE-E**), medium large scale (**POWERICE**) to large scale Organic Rankine Cycle Cogeneration Plants (**ORC-PLUS**). A project aimed to develop Organic Rankine Cycle cogeneration plants using rice straw (**POWERICE**).

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

Few projects 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 industry. 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 (**SteamBio**).

A project investigated the thermochemical conversion of sewage sludge from the pulp and paper industries and integrating it with microbial conversion to produce bio-coal, bio-methane and biochemical. 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 m 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 m from Sustainable Development Technology Canada and $7.0 m 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-catalysic 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 investigate the fundamentals of biomass fast pyrolysis to provide insight in pyrolysis chemistry and to improve the understanding of fast pyrolysis mechanisms and the process and design of reactors (**PYROCHEM**).

An important area of interest included the use development of pyrolysis process that converts solid biomass into a fast pyrolysis bio-oil to be used directly for energy purposes, upgraded to transportation fuels or separated into bio-based chemicals (**Bio4Products**). Integrated biomass pyrolysis with gasification, thermo-catalytic reforming, and hydro deoxygenation processes were investigated for heat and power and for production of fuels (**bioliq**). A pyro-gasification-based process has been investigated (**Hydrogreen**) to convert biomass (wood, wood waste, straw) into energetic hydrogen and decarbonated CO_2.

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. The use of fast pyrolysis bio-oil from different biomass types has been investigated (**SmartCHP**) at small-scale cogeneration engine to produce heat and electricity in an efficient small-scale diesel-engine based CHP (100-1 000 kWe).

Pyrolysis systems using various catalysts have been investigated to improve the catalytic pyrolysis of biomass by the use of novel catalysts, optimization of catalyst selectivity towards desirable high value products (**ECOCAT, FLEXI-PYROCAT**). 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**).

The pyrolysis process of various biomass types (residues, agro-food waste and municipal waste) has been tested for obtaining a mixture of liquids, gases and solids with high energy content (**PYROCRACK**), to produce biochar (**PyroTech**) and for use of fast pyrolysis bio-oil the in residential heating applications (**Residue2Heat**).

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 m^3 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 m of which subsidised €8 m 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.

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.

3.5.7 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.

Several projects addressed the development of the through hydrothermal liquefaction processes to produce a bio-crude oil that 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 (**Hydrofaction, REBOOT**). Some projects investigated the hydrothermal processing for understanding of relation between feedstock and process conditions vs. product yield and quality and efficient valorisation of residual process streams (HyFlexFuel) and to design existing steps and optimize of innovative hydrothermal liquefaction process steps (**NextGenRoadFuels**). 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.

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 hydrothermal carbonisation coal and identifying feasible uses. Several projects investigated the hydrothermal carbonisation for converting organic waste streams into carbon-neutral biocoal, activated carbon, recovered phosphorus, soil remediation material, water, and energy (**HTC4WASTE, HTCycle**) and for sewage sludge treatment into into high value products or as an alternative to spreading on agricultural soil, composting, incineration and anaerobic digestion (**HTCycle, HTSew**). Some attempts aimed to recover carbon from waste (**HTC4WASTE**) through hydrothermal carbonization for converting organic waste streams into carbon neutral biocoal and to obtain high-value carbon products as well as for recovering phosphorous from wastes while generating carbon neutral fuels and a carbon sink in the form of carbon materials (**REBOOT**).

The projects aimed to demonstrate the economic and technological performances of hydrothermal carbonisation 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.

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 m 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**), fluidised-bed gasifiers (**BLAZE**), dual fluidized bed (**COMSYN)** Chemical Looping Gasification (**CLARA**) atmospheric or pressurised reactors, using air or steam gasification, from micro-scale (25 to 150 kW) (**FlexiFuel-SOFC, FlexiFuel-CHX**) to larger scale (250-1500 kWe) (**GAREP)** (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 high temperature gas cleaning system with ultra-low particulate matter, tar and contaminants (alkali) content (**BLAZE, FlexiFuel-SOFC, HiEff-BioPower**) 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. Various projects aied to demonstrate the use of a range of feedstocks from urban agriculture and industrial waste (energy crops, wood pellets, wood chips, agro-pellets, fruit stones/shells, solid recovered fuels, sewage sludge, etc.) (**GAS BIOREF, PHENOLIVE**), including gas cleaning, and handling, preparation, and feeding issues associated. Several project aimed at studying, developing and testing the integration of biomass gasification processes for the production of into high quality syngas with low particulate matter, low tar and contaminants and further use in engines (**PlasmaPower, RENEGAS**), fuel cells (**BLAZE, FlexiFuel-SOFC, HiEff-BioPower, Waste2GridS**), or gas burners (**FlexiFuel-CHX**). Some projects aimed to develop stand-alone biomass gasification system for heat and power, small power ranges a solution for off grid installations (**COSYNAT, PlasmaPower**) for different, low value types of waste streams as feedstock to be used in used into an electrical engines.

Various configurations have been investigated for biomass gasification, syngas cleaning and conditioning and methanol synthesis (**CONVERGE**), flexible sorption enhanced gasification (**FLEDGED**) and integrated hybrid process combining electrolysis of water with gasification of biomass and catalytic liquefaction to produce combined heat and power (**FLEXCHX**). Biomass gasification processes have been investigated to provide sollutions for alternative energy for heat production (**EUWaste**), combined heat and power (**FLEXCHX**) and small biomass trigeneration (**TES**). 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.

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 m 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 MWe. 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 m advanced conversion treatment (ACT) plant, being developed by AssetGen Partners. Green Investment Bank (GIB) and its partner Foresight Group, invested £30 m 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 m.

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 m). 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 €4.5 m.

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. Table 8 provides a selection of RTD gasification plants worldwide.

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 Demonstration sanlagen 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.

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 (**BEAL, SE2B**) to develop and optimize of low input and application-based microalgae culture systems. Several projects aimed to characterise microalgae biomass (**ABACUS, ALGAE4A-B**), or studying the metabolism to get better understand mixotrophic metabolism of microalgae (**MMM-REBIO**), and of novel microalgae in low temperature bioreactors (**MONSTAA**) and for the selection of new, better performing algae varieties (**MAGNIFICENT**).

Several projects aimed to improve algae strains and cultivation techniques to improve the cultivation of the microalgae by photobioreactor improvements, online monitoring and automated control, media optimization, water treatment and recycling (**MAGNIFICENT**), ensuring various microalgae strains cultivation without risking contamination (**INTERCOME**) and investigating photoautotrophic, mixotrophic and heterotrophic microalgae production systems (**ACCORDION, MMM-REBIO**) 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, to increase photoconversion efficiency, to achieve optimal growth of selected strains in photo-bioreactors, and to improve the biomass yield (**ECO-LOGIC GREEN FARM**). Some projects aimed to develop improved photonic materials that can be used to maximise algal growth (**BIOMIC-FUEL**) and scalable photobioreactors design based on mesh-ultra-thin-layer technology (**BIOSEA**). The use of light to maximise algal growth was researched through the development of photobioreactors that provide algae with artificial irradiation and increasing illumination by concentrating and transporting sunlight by optical fibers (**Brevel, BIOMIC-FUEL**).

While the majority of projects focussed on the use of microalgae, few projects addressed the cultivation and use of **macroalgae** (**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 (**MacroFuels**). The research aimed to develop methods tools for reliable analysis and optimization of the design and operation of integrated algae/bacteria consortia (**SALTGAE**).

Various cultivation, harvesting and extraction techniques were tested with microalgae species (**VALUEMAG**). Microlgae harvesting technology, a critical challenge faced by algae cultivation, has been investigated, including flocculating agents, filtration, ultrasound and magnetic nanotechnologies. Several solutions have been investigated on the use of nanotechnologies for downstream processing, production and harvesting of microalgae (**CMHALGAE, VALUEMAG**). Several projects also addressed harvesting and processing of seaweed (**AORTA2**) and for seaweed storage bags allowed storing the biomass at sea and ensiling (**MacroFuels**). 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**). Algae cultivation harvesting and extraction, separation and fractionation/purification of microalgal high-value components (**AlgCoustics, BIOSEA, CMHALGAE, MAGNIFICENT**) techniques were tested to microalgae species, investigating the use of on different pre-treatment and alternative extraction methods, acoustic waves, nanoparticles, pressurized liquid extraction and supercritical fluid extraction, etc.

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 anaerobic digestion.

Algae cultivation for biomass production in real environment with flue gas from heat and power production was addressed in some projects (**BIORECYGAS, ECO-LOGIC GREEN FARM, INTERCOME**) investigating the use of efluents as a source of carbon, required for the photosynthetic process of microalgae to stimulate algae growth. The use of microalgae to remove nutrients from wastewater treatment effluents and recover nutrients (phosphorous and nitrogen) and valuable materials was investigated in several projects from wastewater treatment treatment plants (**IPHYC-H2020**), using high salinity wastewater from the food and drinks industry (**SALTGAE**), wastewater from agricultural, industrial and municipal sources (**INDALG**).

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 m 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 m 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 m grant from Australian Renewable Energy Agency. The plant is the first of its kind in Australia.

Solazyme (now TerraVia) was awarded $22 m 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 m 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 m). **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 m). **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 ($900 k).

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 processes integration, and integration of chemical and biochemical routes into biorefining (**IProPBio**). Some projects focussed on the cascading biorefinery concepts to establish optimal combinations of feedstock, biorefinery, end-products and markets demonstrating new lignocellulosic value chains and valorisation routes for co-products in different process conditions (**BIOFOREVER, BIOrescue, TASAB**).

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. A number of biological/ biochemical processes were investigated, thermochemical (**4REFINERY**) or the integration of hybrid bio-thermochemical process (**TASAB**). 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. The projects aimed to create and demonstrate biorefinery concepts integrating thermal and biochemical conversion pathways into sustainable biorefining such as anaerobic fermentation processes and pyrolysis, extraction and separation processes, production processes integration to obtain desired products (**IProPBio, TASAB**).

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 (**TASAB**) that maximizes energy production from algae for achieving a net positive energy balance. Another project addressed the concept of the cascading marine macroalgal biorefinery (**MACRO CASCADE**) for the generation of a diversity of added-value products using a range of mechanical, physico-chemical and enzymatic pre-processing and fractionation techniques combined with chemical, enzymatic or microbial conversion refinery techniques.

Several projects focussed on the development of marine macroalgal biorefinery, cultivating and refining seaweed biomass in multiple uses for of innovative chemical and biological processes for the extraction of bioactive molecules and value-added products (**GENIALG**), integrating mechanical, physico-chemical and enzymatic pre-processing and fractionation techniques combined with chemical, enzymatic or microbial conversion refinery techniques (**MACRO CASCADE**) and using marine water and nutrients from wastewaters and establish processes for bioproducts extraction to produce biofertilizers and aquafeed (**SABANA**).

Different projects addressed different feedstocks non-food/non-feed material as feedstock, such as wood-based feedstocks and waste wood (**BIOFOREVER, BioMates**), agricultural residues (straw, pruning residues and wastes) (**BIOrescue**), various waste streams (**DEEP PURPLE, ENGICOIN**), but also oil crops grown in arid and/or marginal lands (**FIRST2RUN**).

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 m 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 m) 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 m) 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 m) 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 m 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 bn 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 bn and about €2.7 bn of private investments. Eight projects on bioenergy were selected in the first call for proposals with a total funding of €629 m. In the second call for proposals the six projects on bioenergy were awarded a total funding of €308 m. 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 bn. Four awarded NER 300 projects have been cancelled by the end of 2016, resulting in undisbursed NER 300 funds of at least €436 m. 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. The projects already selected for funding will be implemented, although further calls for proposals under the NER 300 programmee are not planned.

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 bn (€26 bn guarantee from the EU budget, complemented by a €7.5 bn 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 $100 bn 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 bn 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 €7.5 m – €75 m. 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 SET Plan has a key as an EU energy research and innovation initiative to achieve Energy Union goals and to deliver the innovations necessary to achieve the European transition to climate-neutrality by 2050. SET Plan has put forward a dedicated vision for each technology area by setting ambitious targets to be reached and to developdemonstrate and scale up low-carbon energy technologies.

Implementation Plans have been developed for each technology areas to facilitate the achievement of these strategic targets. The 14 Implementation Plans cover all the Energy Union Research & Innovation priority areas and the SET Plan 10 Actions. In order to execute the Research & Innovation activities included in the Implementation Plans, Implementation Working Groups (IWG) have been established to to monitor the progress of actions under the Implementation Plans and to advance the respective Implementation Plans.

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 Implementation Working Group (IWG) has been established on the Action 8: Bioenergy and Renewable Fuels for Sustainable Transport to monitor the prograss and and enable the achievements of the Research and Innovation actios, to support the development, demonstration and scale-up to achieve technical maturity and commercial availability of various conversion technologies.

The priority R&I activities are essential for achieving the SET Plan targets for renewable fuels, bioenergy and intermediate bioenergy carriers. 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 Research and Innovation (R&I) actions include clear targets related to the improvement of process efficiency of conversion to end products, improvement of GHG savings and reduce conversion system costs. The R&I activities includes 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: EU projects

A number of 79 projects have been identified as addressing general bioenergy issues under H2020 RTD EU programmes.

The overall purpose of **AfriVeg** project is to develop methods for an improved assessment of African vegetation resources based on new capabilities originating from satellite passive microwave observations. By combining multi-frequency VOD retrievals with long-term VI datasets, in situ measurements, and DGVMs, this project will accurately quantify woody biomass, green biomass, net primary production (NPP), vegetation phenology and ecosystem functional types (EFT) in Africa, as well as their long-term changes and the climate and socio-economic drivers. The results allows an improved vegetation resource management in Africa and understanding of global carbon cycling.

This **AgRefine** European Training Network (ETN) integrated training programme will facilitate the amelioration of Europe's agri-sector competitiveness and environmental sustainability challenges by creating new and optimising current agri-resource and agri-waste valorisation pathways. The ETN will consist of 15 highly interdisciplinary and inter-sectoral PhD projects, each specialising in specific aspects of the bioeconomy, and provide training in a number of cross-cutting multi-disciplinary and highly interdisciplinary advanced technical subject areas including chemical and process engineering, biological science, life cycle assessment, and economics. The network will combine assessment of legislation and policy as it applies to the bioeconomy, with industry-led innovation of AgRefine technology, and market-led experience of sustainable value chain creation.

The project **AGRIFORVALOR** aimed to connect a range of stakeholders in order to achieve new value chains, and stimulate biomass sidestream market uptakes into value-added products. The focus of the project was the transfer of know-how and information to enable and support farmers and foresters to exploit existing research results and the facilitation of business model development for new bio-industry start-ups. In the project, an overview of valorisation techniques and good practice cases is facilitated through the sidestream value tool making this information easily available for stakeholders such as foresters, farmers, the biomass processing industries, the bio-energy sector but also for the research sector. The project developed end-user materials and tools for farmers and foresters enabling knowledge transfer and capacity building enabling farmers and foresters to become active partners in the biomass sidestream value chains, contributing to awareness raising, networking and innovation especially in the hubs.

AgroCycle project proposed to convert low value agricultural waste into highly valuable products, including wastes from several agricultural sectors: wine, olive oil, horticulture, fruit, grassland, swine, dairy and poultry. This will be achieved by developing a detailed and holistic understanding of the waste streams and piloting a key number of waste utilisation/valorisation pathways. It will bring technologies and systems from ~TRL 4 to ~TRL 7 within the 3 years of the project. A post-project commercialisation plan will bring commercially promising technologies/systems to TRL8 and TRL 9.

AGROinLOG aims to improve the competitiveness of agro-industries through their transformation into Integrated Biomass Logistics Centres (IBLC) that takes advantage of the facilities of an agro-industry, its network of contacts and its own residues or non-used local resources to create new activities during idle periods and obtain new bioproducts. AGROinLOG tests and demonstrates the IBLC concept in three real agro-industries. These pilots develop a new logistics chain and adapt the existing equipment to the new production schemes. This implies executing integrated harvesting activities, integrated logistics, integration of non-food biomass into the current food facility, and performing equipment compatibility trials and tests to validate the new products by final consumers.

AgroPellet developed a prototype for a pelletising machine which is able to process all kinds of agricultural residues occurring in Europe as well as mixtures of these residues and further organic residues not directly deriving from agriculture, e.g. from food processing. All these residues can be processed with just one machine and without any modifications in the hardware of the machine. Several technological developments are necessary, the market potential has to be confirmed and a commercialisation concept has to be developed to obtain a marketable machine. A feasibility study was conducted to assess the technological and economic feasibility of the pelletising machine and an initial business plan was developed as a basis for its commercialisation.

ALTERFOR's goal is to facilitate the implementation of better forest management models (FMMs) to secure the capacity of Europe's forests to continue providing balanced ecosystem services: 1) Identifying and developing FMMs robust in their capacity to deliver ecosystem services and overcome projected socio-ecological risks and uncertainties; 2) Assessing the impact of different FMM combinations in terms of resultant ecosystem services on the European and landscape level, and 3) Facilitating the implementation of desired FMMs and improving cross-national knowledge transfer regarding their benefits, costs, management, and utilization. ALTERFOR developed a common ontology to harmonise the description of the FMMs, describing such facets as intensity and frequency of various silvicultural interventions covering: (a) the way the FMMs are applied in the specific regions; (b) relative ranking of FMMs with respect to their capacity to deliver selected ecosystem services; and (c) so-called technological landscapes describing the required and available knowledge, technologies, labour and economic factors.

The **Ambition** project aimed to develop a long-term joint European Community Research and Innovation Agenda (ECRIA) 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. The AMBITION activities were based on national research agendas and programs from ETIP and EERA Bioenergy relying on three key unit operations in the production of liquid biofuels (pre-treatment and fractionation, gasification and syngas fermentation) and on linking of energy systems (grid electricity and biofuels) to improve overall efficiencies.

Amicrex 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 through a microwave intensified microemulsion extraction process. The AMICREX concept can be extended to address the challenges proposed by extraction of nonpolar metabolites from other renewable biomass sources (e.g. Microalgae). The project focuses on the evaluation on the laboratory scale microwave cell disruption and subsequent microemulsion extraction processes of the characterized biomass. Based on the so obtained process and system specifications the small scale process is aimed to be turned into an industrial design concept through process modeling and simulation.

This **BESTF3** ERA-NET Co-fund brings together a number of national&transnational organi-sations 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. The overall aim for this BESTF3 ERA-NET is to implement a joint programme for bioenergy demonstration projects to demonstrate enhanced bioenergy technologies that will help Europe progress towards achieving its 2020 targets, leveraging public-private partnerships to manage the risks and share the financing of close to market bioenergy projects.

BestRES aimed 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. The BestRES project investigated current market barriers and suggested ways of improving the role of renewable energy aggregators for the future to implement best practices already tested in various European countries to boost the integration of renewable energy into the market. The partners identified, reviewed and optimised 13 pioneering business models that enable energy aggregators to successfully participate in the market by combining renewable energy supply, energy storage, flexible demand and ICT technologies into a commercially viable product. The project also identified technical, market, environmental and social benefits as well as legal and regulatory barriers preventing their successful implementation.

BIAR has developed a process for treating low-value biomass to remove the ash content and provide high quality feedstocks. BiAR is a chemical proccess to remove the ash content from ash-rich lignocellulosic (e.g. bark, rice husks) up to 95% biomass or sludge digestate, that consists of 3 differentiated steps: 1) liquefaction of the organics through solvolysis, 2) ash content separation through filtration, and 3) recovery of solvents through distillation. The process entails solvolysis a solvent and catalyst treatment at at moderate temperature (200 °C) and pressure to break down biomass into smaller organic elements and compounds. The second phase employs mechanical filtration at high pressure to remove the larger inorganic compounds. The remainder of the distillate contains pure ash-free organic matter, which is chemically identical to the original biomass material, minus the ash. The BiAR process has many possible applications from large scale pellet production to sludge treatment and from specific ash recovery to laboratory experiments for investigating the properties of pure biomass.

BilletPro addressed a developed prototype for a harvesting machine for plantations of fast-growing trees, so-called short rotation plantations (SRPs). A first technical prototype has demonstrated the proper functioning and huge potentials of the technology. However, improvements and adaptations are required to achieve the market breakthrough. In this BilletPro project a feasibility study will reveal the technical feasibility of the envisaged improvements and the optimal way of implementation, while a business plan will show the optimal way of commercialisation. An innovative new developed harvesting technology enables a fast drying of the wood without any losses of the energy content.

The goal of the **Bioenergy4Business** project was to support and promote the substitution of fossil fuels used for heating, by bioenergy sources (industrial waste, forest biomass, straw and other agri-biomass). The Bioenergy4Business project' main focus was to create demand for mid-scale biomass heating systems within selected heat market segments. B4Bs objectives were to increase the use of solid biomass, to support the application of sound business models and the careful assessment and implementation of biomass heat applications in selected heat market segments. The main technologies which were investigated by the B4B project were solid biomass heating plants for supplying low temperature, either individually, in-house or via a district grid. B4B focused on the mid-scale power range (0.1 to 20 MW nominal heat load) using wood-chips, wood pellets or straw. Existing bioenergy business models, regulations, support schemes and policies were assessed. B4B advised public authorities about policy measures which are applicable to speed up the diffusion of bioheat technology by creating a more investor friendly environment.

The **BioEnergyTrain** project aimed to foster European cooperation and to address identified knowledge gaps across the whole bioenergy value chain through common training collaboration and best practices. It also aimed to bridge the gap between industrial innovation and education to improve the practical orientation of higher and professional education to enable the market up-take of innovative solutions and to create a network of integrated research and industrial infrastructures and develop programmes on the integration of practical training modules at these installations in curricula. BioEnergyTrain developed and implemented multiple cooperative educational formats to become role-models for practice-oriented education. These include the two master curricula BRE and BVM with the BET courses, the developed Professional Educational Formats, as well as internships, master theses and design case work.

The **BIOFIT** project aims to facilitate bioenergy retrofitting in five industries: first-generation biofuels, pulp and paper, fossil refineries, fossil firing power and combined heat and power plants. BIOFIT performed an overview of existing options for retrofitting, and best practices analysed, to establish (both technical and non-technical) success factors for the development of 10 concrete bioenergy retrofitting proposals industry-driven and the establishment of dedicated working groups for each industry (industry platform) to facilitate dialogue. Retrofitting means often lower capital expenditure (CAPEX), shorter lead times, faster implementation, less production time losses, lower risks and therefore faster project development and increased market benefits.

The overall goal of the **Biomasud Plus** project was to develop integrated solutions to promote the sustainable market for Mediterranean solid biofuels for residential heating by developing a quality and sustainability certification system, assessing the existing barriers and identifying solutions with emphasis on the sustainability and quality control systems and developing tools and databases with information about sustainable biomass resources. A market study was made for the Mediterranean residential heating solid biofuels that led to a roadmap targeting the development of a sustainable market for emerging solid biofuels. Technical and economic performance of current residential heating boilers and stoves tested as well as combustion test runs BIOMASUD PLUS fuels have been taken into account for elaborating the guidelines for boilers and stoves manufacturers, installers and users.

The **BioPellets** project proposed the integration of food waste grease into biopellets, in an 80-20 biomass-grease mix. This improves the energy content of the pellets by 27%, beating out coal, and reduces the cost of production by up to 50%. Food waste grease can have a serious impact on urban environments and aquatic ecosystems, blocking and damaging sewer piping, as well as generating a high biological oxygen demand if it is released to ground water or to open watercourses, damaging aquatic plant and animal life. The project carried out a thorough assessment of our value chain, identifying key stakeholders and establishing a business model to support their integration of our product, into their product ranges.

The **BIOPLAT-EU** project promotes and supports the uptake of sustainable bioenergy projects on marginal, underutilized and contaminated lands (MUC lands). The project promotes and informs about the opportunities to produce biomass for non-food purposes through a web-based platform that assesses the environmental, social and techno-economic sustainability aspects of defined value chains for bioenergy production on MUC lands. The project also supports stakeholders and give guidance on how such projects can be implemented. The project will link biomass producers and processors with investors and will guide them on how to make their projects bankable.

The **BIOREG** project aimed to improve wood wastes valorisation (from construction, demolition and renovation works, furniture, packaging and civil engineering) throughout Europe by acting all along the value chain. In this purpose, the project intends to facilitate dissemination of good practices and favorable environments from model regions towards regions where is existing an unused potential of wood wastes. BIOREG will create a platform of stakeholders that aims to facilitate cooperation and collaboration between stakeholders and in the end promote replication in recipient regions. The project assessed success factors in so-called model regions and weaknesses in regions where an unused wood wastes potential is observed.

BioRES 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 identified the locations for new BLTCs, assesses regional potentials for the production and use of bioenergy, and initiates stakeholder dialogues involving producers and users of bioenergy. BioRES increased market uptake of domestic supply chains for quality-controlled woody bioenergy products, from sustainable forestry and wood residues, by means of developing BLTCs as regional hubs. At the end of the project, 9 BLTCs were created of which eight centers with physical infrastructure and one, a web-based BLTC. In parallel to the establishment of the BLTCs, BioRES offered continued support in increasing quality assurance and sustainability of biomass.

The objective of **BIOSURF** was to increase the production and use of biomethane, for grid injection and as transport fuel, by removing non-technical barriers and by paving the way towards a European biomethane market. BIOSURF conducted national and international studies of feedstocks available for biogas and biomethane production. The project looked at the potential of starch-rich crops, animal waste, other organic waste materials, residues and catch crops. The team investigated the impact of current, as well as potential, pathways for these feedstocks. The project also compared and promoted biomethane registration, labelling, certification and cross border trade practices in Europe, to facilitate cooperation. The project compiled a list of policy recommendations that could improve the sustainability of raw material supplies, the use of biogenic waste, and the biomethane trade overall. The project established a European Renewable Gas Registry (ERGaR).

The purpose of the **BioValue** project was to enable quality determination of biofuels in real time through the development of a novel biomass scanner for measurement of various types of biomass. The project developed a new modularized architecture for multisensor biomass scanners and has completed detail design of several generic modules. The new modules have enabled a fast design and build of a new multisensor biofuel sample analyzer that has been used in comprenhensive research activities, measuring moisture content, ash content and energy value for logging residues, roundwood chips and sawdust. The project developed the MxS scanner based on a more light weight approach that is is significantly less complex than the Flow Scanner but still with capability to prove the overall purpose of the project.

The **BioVill** project aimed to develop regional bioenergy concepts in several countries up to the investment stage in order to become “bioenergy villages”. Bioenergy villages have successfully emerged in Austria and Germany, combining market orientation and sustainable energy supply at the municipal level by involving all societal stakeholders. BioVill transferred and adapted these experiences to other countries and developed regional bioenergy concepts. The project provided modern planning and calculation tools and strengthened partners’ capacities for assessing technological and economic viability of development options. As a result, suitable technical solutions and business models have been elaborated for each of the target villages. Furthermore, BioVill supported dialogue with local and national politicians and cooperation between different policy areas to optimise the regulatory framework and better implement EU legislation.

CarbonOrO has developed an innovative low energy and low cost technology to capture CO2 from gasses. Current applications are in biogas upgrading and the production of CO2. Future use may include the capture of CO2 from flue gasses at e.g. power plant, followed by underground storage, in order to mitigate climate change caused by burning fossil fuels. CarbonOrO offers a containerized and standardized, low-temperature amine process that can easily be adapted, sized and installed. Thie project enabled CarbonOrO in exploring international markets and promising business cases for carbon capture in the evaluation of the required specifications and characteristics of these applications with potential partners and/or clients and in the elaboration of a detailed business plan.

CarboPlex project aims to investigate and exploit the potentials of a new material termed biochar-mineral complex (BMC) using common waste streams to produce BMCs with distinct properties. Primary target is the use of BMCs as soil amender, especially in soils, where the delicate but crucial structure of organo-mineral complexes is threatened by unsustainable soil use or climate change. Biochar-mineral composites (BMC) have been produced from organic wastes (i.e. sewer sludge, compost-like output) and mineral substances (wood ash, lignite coal ash, natural zeolite) by means of pyrolysis and hydrothermal carbonization (HTC). The work expended the current state of knowledge on co-carbonization of organic and mineral materials into biochar-mineral composites (BMC). The findings have an economic potential as they show the possibility to produce carbon materials from wastes that are considerable less phytotoxic than their precursors.

The **CARGOMIL** proposed an innovative self propelled all terrain vehicle for mobilising large quantities of biomass such as wood, agro waste and herbaceous biomass (bio raw material) for producing a tradable biomass format (briquette) with a better storability and longer lifespan delivering a higher economical and energetic value. Over the densification bundle aiming to produce pellets-briquettes, a specific feature will be an integrated process for biomass hydrolyzing and converting the biomass in situ into syrup with high sugars.

COREGAL developed a low cost unmanned aerial platform and service for biomass mapping will allow wide scale mapping in the Brazilian context of forest management, which is of high interest for bioenergy. A first of a kind combined Position-Reflectometry Galileo receiver has been developed as main sensor for platform positioning and biomass estimation, the latter using reflected Global Navigation Satellite Systems (GNSS) signals (also called GNSS-R) that propagate through tree canopies, branches and leafs. Test campaigns have been performed to validate the COREGAL platform and approach, including comparison and combination with satellite-derived data to improve accuracy of local biomass maps.

The project **COSYNAT** proposed a stand-alone solid biomass to heat and power gasification system for small power ranges. COSYNAT is cost effective, versatile and less polluting solution. The project aimed to take the technology from TRL 6 to TRL 9 and to commercialize it, at small scale, variable feedstock operation to produce syngas with low tar and ash with low CAPEX and low OPEX. COSYNAT is also a solution for off grid installations at low electricity production costs when biomass is readily available. A business plan has been done to complete the COSYNAT marketing strategy.

The **DEPURGAN** project aims to bring to the market an efficient pig manure treatment process, with an initial investment 4 times lower compared to other solutions and competitive operation costs. DEPURGAN developed and patented a pig manure treatment system that's tailor-made to accommodate the needs of users, fully automated, expandable and can be implemented on one or more farms. The system performs a succession of physical-chemical treatments known as depuration that includes homogenisation, solid-liquid separation by centrifugation, coagulation-flocculation and solid-liquid separation by electrocoagulation. The treatments help to obtain two residuals: a solid used for the manufacturing of pellets, with an equal mixture of manure and pine wood and the liquid residual is used for fertilisers in agricultural crops.

DIABOLO aimed to strengthen the methodological framework towards more accurate, harmonised and timely forest information to enable the analysis of sustainable biomass supply derived from national forest inventories and facilitate near real-time forest disturbance monitoring. The project involved over 100 experts from 25 European countries that provided new methodologies for more accurate, harmonized and timely forest information used for the EU policy processes, international reporting obligations, forest administration and forest planning as well as for global monitoring systems such as REDD+, FLEGT and UNFF. The project produced list of policies relevant for sustainable multipurpose forestry at EU level, demand of forest information by policies, data demand and data provision, and strategies for improving information exchange. It developed harmonisation measures for comparable stem volume estimation that improves the consistency of volume and biomass statistics. The project contributed towards estimates on biodiversity and conservation status indicators, production of non-wood forest products, forest hazards indicators and social indicators.

The **DiBiCoo** project aims to support the European biogas/biomethane industry by preparing markets for the export of sustainable biogas/biomethane technologies from Europe to developing and emerging countries. This will be achieved by the development and application of innovative digital and non-digital support tools and actions, by knowledge transfer and capacity building as well as by the preparation of demo cases up to the investment stage. DiBiCoo aims to support the European biogas industry in diversifying its sales market and therefore increasing the deployment of **biogas technologies** in emerging markets across Latin America, Africa and south east Asia, helping mitigate GHG emissions and increasing the share of global renewable energy generation.

The **DRALOD** project aims to develop an energy recovery plant from food waste based on an energy efficient heating systems optimising the combined operation to the level of achieving cost-effectiveness in the drying of waste. The solution proposed is an innovative low-temperature air drying plant using renewable energy sources (solar and biomass air heating) as well as heat recovery for increased energy efficiency, using a temperature process demonstrated to be reliable for eliminating pathogens while preserving nutrient content. The project team designed a DRALOD drying plant, integrating a biomass heating system with high flexibility on both type of fuels / fuel quality and mode of operation to enable low operational costs and a smart controller unit for a combined solar-biomass drying plant based on thermodynamically simulation of multidomain dynamic system.

The **EcoBioMass** project aimed 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 optimization of the EcoBioMass concept gowe beyond the state-of-the-art by the introduction of semiautomatic harvesting and handling of small diameter trees. The project has completed the optimization and validation of the individual modules of the concept followed by the actual use and demonstration of the new concept.

The project **EFFORTE** aimed to develop and adopt novel technology and tools that improve efficiency and sustainability of forestry and throughout the entire forest based value chain within EU. The project established field experiments and made wheeling tests to develop a techno-economically feasible methodology to predict trafficability of the forest stands prior to forest operations. It also accomplished field experiments on automatic soil preparation, early pre-commercial thinning, pre-commercial thinning, optimization of regeneration and young stand management regimes and acceleration of forest growth by precision forestry procedures. The project also developed and tested methodology to predict yields of the incoming forest stands based on historical harvester data records using "Big Data' (geospatial and data from forestry processes).

The main goal of **ENABLING** was to support the spreading of best practices and innovation in the provision (production, pre-processing) and creating appropriate conditions for the development of efficient biomass to BBPs (Bio-Based Products and Processes) value chains. Upscaling biomass production and pre-processing, and combining streams towards the BBPs with those of more traditional bioenergy chains would enhance biomass production gains scale to meet higher demand in bioenergy and the BBI, reinforce biomass supply and contribute to job-creation. The project looks at future developments, with the consolidation, in a self-sustainable way, of the innovation brokerage platforms after the end of the EU funded initiative.

The objectives of the **Enerbox** study were to perform a technical, commercial and financial evaluation of the project, where key issues related to IPR, technical development needs, market opportunity and commercialization strategy, financial simulations, etc. Energox provides an autonomous (operable off-grid) efficient and low cost solution for users with both a high thermal energy need and difficult access to the grid (medium-large farms, mushroom cultivation, isolated buildings or communities) for off-grid applications that require a reliable source of thermal energy. This is an optimized system design adding PV to a standard 100 kW biobox (biomass portable solution) compact and easy to transport, adding oxyhydrogen to the biomass boiler increasing efficiency by at least 25%.

The general objective of this **ENERCOVERY** project was to place in market a breakthrough energy technology for pellet manufacturing valorising waste by means of a modular and portable gasification-CHP plant installed in their facilities. The goal of the ENERCOVERY project was to confirm the economic advantages of the electrical and thermal energy produced by the implementation of a gasification-cogeneration heat and power (CHP) plant in the pellet manufacturing process. The ENERCOVERY is a suitable technology for low quantities organic waste from any industrial sector that could also be applied in the biomass industrial wastes treatment. The project developed a technical analysis on the viability of the implementation of a gasification-CHP plant in pellet manufacturing process and a business plan.

The **ERIFORE** action aimed to coordinates, complements and updates the information of the major European research infrastructures in the field of the new forest biomass based products and processes and to develop and commercialise novel biorefinery process concepts for producing value added chemicals and materials from forest-based raw materials. The goal was to create a research and innovation infrastructure co-operation platform to optimise use of forest biomass sustainably and cost-effectively through new processes and concepts. The European Strategy Forum on Research Infrastructures (ESFRI) identified research infrastructures (RIs) that creates a bridge between science and innovation, developing and commercialising novel biorefinery process concepts for producing value added materials and chemicals from lignocellulosic raw materials. The

ESFRI study mapped research needs and drivers, the availability and development needs of existing RIs, and collaboration in the field of circular forest bioeconomy and outlined initial business models, financing plans and governance structures.

ETIP Bioenergy-SABS aimed to support the contributions of biofuel and bioenergy stakeholders to the Strategic Energy Technology (SET)-Plan. The ETIP Bioenergy-SABS role consisted in connecting all stakeholders from industry, politics, research and development. It monitored the bioenergy and biofuels sector, provided information on biofuels/bioenergy and recent trends, facilitated discussion between various groups, and provided overviews and summaries on stakeholder views to the working groups of the ETIP Bioenergy Platform. The project compiled scientifically sound, fact-based information on technical and non-technical biofuel and bioenergy issues. The platform merged the European Biofuels Technology Platform (EBTP) and the European Industrial Bioenergy Initiative (EIBI). The project also contributed to the drafting of the implementation plan for the SET-Plan's Action 8 on Renewable Fuels and Bioenergy that suggests concrete R&I activities and proposes relevant funding opportunities for their realisation.

ETIP-B-SABS 2 will support and empower renewable fuel and bioenergy stakeholders' contributions to the Strategic Energy Technology (SET)-Plan. The project´s objective is to support ETIP-Bioenergy in this task. Specific objectives are to facilitate the following activities of ETIP-Bioenergy: contributions to the SET-Plan activities and to the Strategic R&I Implementation Plans; collaboration and interaction with other relevant initiatives addressing renewable fuels, decarbonisation of transport, bioenergy and biomass valorisation/ bio-based value chains; constant provision of scientifically sound, unbiased, up to date information on the status of the renewable fuels and bioenergy sector; engagement with stakeholder assistance to the EC and MS in defining research programmes, financialial instruments.

The objective of **FACCE SURPLUS** was 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). FACCE SURPLUS implemented other joint activities such as organizing workshops, scientific events, clustering of research platforms and infrastructures in the field of food and non-food biomass production and transformation systems, and also additional joint calls without EU cofunding. It started implementing its monitoring and communication procedures for the 14 projects funded in the frame of the co-funded call.

The **FLEXYNETS** project aimed to develop, demonstrate and deploy a new generation of intelligent district heating and cooling networks that reduce energy transportation losses by working at "neutral" temperature levels integrating reversible heat pumps and that can provide contemporary heating and cooling. FLEXYNETS proposed solutions that integrate effectively multiple generation sources (including high- and low-temperature solar thermal, biomass, PV, cogeneration and waste heat) where they are available along the DHC network, by managing energy at different temperature levels and assuring optimized exergy exploitation.

FORBIO had the goal to 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. This entailed developing a methodology to assess bioenergy production potential on available "underutilised lands" (contaminated, abandoned, fallow land, etc.) at national and local level. FORBIO carried out several feasibility studies in selected locations to set the basis for building up local bioenergy value chains, techno-economic feasibility studies for the case study areas and best practices for bioenergy policy, regulations and support schemes. FORBIO aimed at encouraging European farmers to produce non-food bioenergy carriers, as bioenergy offers an alternative productive use of the lands where the biomass is not used for food or feed production but for energy purposes.

The **GasFermTEC** project aims to recruit an experienced researcher and research manager, to act as an ERA Chair. It will lead to solutions to capture carbon through bio-based production of fuels and high-value chemicals from globally available feedstocks, including waste gases and syngas produced via gasification of municipal waste and biomass; an initiative that will positively contribute to the Environmental Challenges and to the Smart Specialisation Strategy of Estonia. The ECB Pilot Plant project for the industrial optimization of bioprocessing technologies that, combined with a training and competence centre, will provide the local bioprocessing industry with research-based innovative technology solutions.

The objective the **GRACE** 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 optimize biomass value chains and 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 consortium established field trials at three different scales: plot (by hand), field and full commercial scale (using machines). Industrial partners are preparing equipment for larger scale tests with hemp and miscanthus feedstocks and making good progress in setting-up and building new demonstration plants.

GreenCarbon goal is to develop new scientific knowledge, capability, technology, and commercial products for biomass-derived carbon materials. This is accomplished through research and training programmes for early-stage researchers that covers all aspects from raw material (biomass) to processing (thermochemical conversion, porosity development, chemical functionalisation) and application (e.g., CO_2 capture, heterogeneous catalysis and chemicals from biomass). Preliminary studies were done to establish the most appropriate characteristics of intermediate pyrolysis and fast pyrolysis at laboratory scale, developing a comprehensive pyrolysis/carbonisation model. A number of experiments was already conducted at lab and pilot-plant scale to produce engineered hydrochars or pyrochars through an HTC process or a cascaded HTC-fast pyrolysis process to set the most appropriate operating conditions. Pyrochars have been activated to be used as low-cost and sustainable catalysts for cracking and reforming of pyrolysis vapours. Several experimental studies are being conducted to assess the effect of biomass feedstock and pyrolysis conditions on the carbon sequestration potential of biomass-derived carbons.

The **greenGain** project aimed to strengthen the energy production of woody and herbaceous biomass from nature conservation and landscape management, but not from energy crops. The project developed strategies to build up reliable knowledge on the local availability of these feedstocks and know-how on issues ranging from logistics to storage and sustainable conversion pathways for the transformation of biomass from from nature conservation and landscape management to heat and power. The project also addressed political, legal and environmental aspects in model regions. General guidelines were drawn up together with a handbook on biomass from landscape conservation and maintenance work supply chains tageting regional and local groups responsible for maintenance and conservation work.

GRIDSOL proposed to develop Smart Renewable Hubs, where a core of synchronous generators (CSP and biogas combined cycle HYSOL) is integrated with PV under a dynamic control system (DOME), self-regulating and providing ancillary grid services thanks to firm, flexible generation on a single output, tailored to a specific location, relieving pressure on the TSO. The project developed a methodology for the assessment of Smart Renewable Hubs Implementation and developed an advanced control Dynamic Output Manger of Energy (DOME) to ensure operation efficiency and grid stability with higher RES penetration, and a multi-tower concept for CSP cost reduction and efficiency improvement, to provide secure, clean and efficient electricity by getting the most of each renewable primary source.

HarvPell aimed to the market a solution for stalk-type biomass harvesting and pelleting in one single machine. This feasibility study attempted to define the viability of the project from a technical, commercial and financial point of view, considering the freedom to operate for our technology, defining the tasks and the resources needed, the potential customers, the size of the market and the impact that the project will have. It is an all-in-one self-driving machine pilot remotely controlled able to harvest and pelletize 16t/h. The machine will save work steps during the pelleting process, saving up working time, reducing pre-pelleting transportation costs, and reducing compressing and storage costs when compared to straw bales.

The **Hybrid – BioVGE** project has the primary objective of developing and demonstrating a highly integrated solar/biomass hybrid air conditioning system for space cooling and heating of residential and commercial buildings driven by heat, using two renewable energy resources: solar thermal and biomass. The proposed system will be composed by a number of major components, including solar collector field, biomass boiler, thermal energy storage unit using PCM, thermally driven variable geometry ejector chiller, heat distribution and intelligent integrated control system. An intelligent energy monitoring and control unit will lead to efficient operation of its components. A TRL of 7 for the Hybrid – BioVGE system will be achieved by the end of the project.

Within **ICT-BIOCHAIN**, two of high potential Model Demonstrator Regions serve as test bed locations for the development of Digital Innovation Hubs (DIH) for biomass mobilisation. ICT-BIOCHAIN will build on the work done in improving forestry biomass supply chains through integration of ICT tools, transferring state-of-the-art and new ICT, IoT and Industry 4.0 solution to region specific biomass supply chains. To ensure commercial opportunities are realised, the project builds on ongoing regional bioeconomy developments and opportunities identified in existing Investment Readiness Analyses carried out for the Model Demonstrator Regions. The project platform has defined including the metadata model and it will serve as the first-of-its-kind to store and share the information including regional biomass and waste resources, the potential sustainability and efficiency improvement to be made, and the state of the art of ICT, IoT and Industry 4.0 solutions. The platform serves as a prototype, which will be tested and ready for further development to reach industrial operation level after the lifetime of the project.

The **iMETland** project aims to construct and validate a full-scale application of a eco-friendly device to treat urban wastewater from small communities at zero-energy operation cost, integrating Microbial Electrochemical Technologies (MET) with the biofilters used in constructed wetlands. iMETland outperforms classical biofilters from constructed wetlands by using electroactive bacteria in combination with a innovative electroconductive material to achive depuration rates that are 10-fold higher than classical techniques. Combining electroactive bacteria with electroconductive material has resulted in depuration rates that are 10 times higher than with traditional techniques.

The **InBPSOC** project will investigate the effects and driving mechanisms of innovative cropping systems on biomass production and SOC stocks simultaneously based on ongoing long-term unique field experiments on innovative cropping systems. The key objective is developing innovative cropping systems that allow to protect and increase SOC stocks while increasing biomass production under climate change. Results from the current study will provide crucial information for policy developments and will contribute to the development of sustainable cropping systems for farmers of the future.

The **ISAAC** project purpose was to remove non-technological barriers, such as low public acceptance, insufficient coordination for biogas facilities diffusion, regulatory inadequacies to support biogas/biomethane market penetration in Italy and to make plants implementation easier. ISAAC produced a state of the art of the technology and of the plants for biogas/biomethane production and gas grid injection in Italy and an inventory of biomass and biomethane plants by size type, feedstock, work progress, type of problem faced and local opposition monitoring through surveys, of the social acceptance. The project produed two public participatory processes with representatives of the municipality, the enterprise and citizens to reduce social conflict and to include all actors in important common decision making process.

The **ISABEL** project aimed to strengthen the development of sustainable biogas production-consumption systems by introducing Social Innovation and engaging stakeholders at regional/local level for promoting, stimulating and supporting the creation and operation of community energy initiatives. The project analysed the biogas landscape in the targeted countries to map the relevant policies, incentives, operational practices and regulatory/licencing framework and reviewed the good practices, tools and key factors that facilitate or hinder for Social Innovation and Community

Energy approaches. The project analysed public perception on biogas, its benefits and implications and developed of a pool of Social Innovation and Community Energy approaches with an application potential on Biogas in each of region. The project supported 9 communities them to define their vision and strategy including an initial action plan towards the setting up and operation of energy communities.

KeepWarm addresses intensively with district heating systems in seven countries (i) to increase the energy efficiency of these systems; and (ii) to reduce greenhouse gas emissions by promoting a switch from fossil to renewable fuels. This is most urgently needed in the case of large-scale DH systems that are mostly found in Eastern Europe, the focus of this project. Relying on district heating systems for heat generation is the most effective solution in densely populated areas. However, many district heating systems are highly energy inefficient and need to be modernized.

Breeding and cropping research is performed in the **LIBBIO** project for maximizing the yield and value of lupin agriculture in different European marginal lands conditions. The Andes Lupin grows well in marginal lands, having the ability to fix nitrogen, mobilise soil phosphate and have low nutritional requirements for cultivation. Pre-industrial processing is developed and optimized for the lupin, properties of the different fractions analysed, their advantage for different industrial use evaluated, and a few products developed as an example. Firstly, the focus has been on breeding and selecting suitable varieties for European conditions, seeds have been propagated of many varieties and the first cropping trials performed in seven European countries with very different conditions. Protocols for Lupinus mutabilis cropping have been developed.

MAGIC aims to promote the sustainable development of resource-efficient and economically profitable industrial crops grown on marginal lands. A first version of MAGIC-CROPS database has been developed including data on several industrial crops with information on their agronomic characteristics, input requirements, yield performance and quality traits for end-use applications. In parallel, current and future marginal lands in Europe are being mapped, characterised and analysed to provide a spatially explicit classification that will serve as a basis for developing sustainable best-practice options for industrial crops. The most promising crop species are being identified and new breeding tools and strategies are directed towards better varieties, the identification and optimization of appropriate agronomic practices with limited input and the development of suitable harvesting strategies and logistics to optimise the biomass supply-chains.

MOBILE FLIP project focused on mobile technologies for small-scale processing. Mobile, small-scale systems developed for at site treatment of spatially scattered raw material sources for compaction and/or thermal conversion. In some cases, it might be feasible to transport raw materials to the production site. Using the electricity grid at a plant instead of a diesel generator in the field is beneficial from an environmental point of view. A total of five technologies were identified as having real potential: pelletising (compressing biomass into a useable pellet); hydrothermal pre-treatment for saccharification; hydrothermal carbonisation and torrefaction for fuel; and slow pyrolysis (resulting in biochar). These technologies were then successfully demonstrated in continuous mode operation by industrial partners using selected raw materials and environmental, economic and legislative evaluations were also carried out.

MOVARC is a new thermodynamic cycle (inspired in both Rankine and Stirling cycles) coupled to an innovative transmission design working to generate energy from industrial waste-heat and other mid-level renewable heat sources such as biogas. MOVARC does not require a turbine for energy generation, instead it relies on a transmission system and lineal work outputs. MOVARC cycles transform mid & low-heat resources (industrial waste-heat or biogas) into energy at higher efficiency than current technologies including organic Rankine cycles, Kalina cycles, and Supercritical CO_2 cycles.

The **MUSIC** project aims to improve market uptake of three Intermediate bioenergy carriers (IBCs) – pyrolysis (bio-oils), torrefaction (solid products) and microbial oil. IBCs can be used directly for heat or power generation or further refined to final bioenergy or bio-based products. MUSIC aims to facilitate further market uptake of three types of IBCs by developing feedstock mobilisation strategies, improving logistics and development of IBC trade centres. It will do so by developing feedstock mobilisation strategies, improving biomass logistics and developing IBC trade centres. Project results are to include – besides direct market uptake due to the case studies, practical guidance to market actors and advice to policy makers serving as input for more informed policy, market support and financial frameworks.

The **NewCat4Bio** project aimed the preparation, characterization and application of (hydro)thermally stable, homogeneous, and porous metallosilicate catalysts for biomass conversion applications. The research work included synthesis for the preparation of homogeneous, (hydro)thermally stable and porous mixed metal oxides. Characterizationtests included some routine analysis of mixed metal oxides as well as advanced and original characterization experiments (especially surface characterization). These catalysts were characterized by an array of advanced physico-chemical tools to evaluate the effects of preparation parameters on the desired properties – homogeneity, hydrothermal stability and texture. Catalytic testing was completed first by mounting (revamping) of the catalytic reactor and learning how to set the correct parameters for catalytic reactions.

The goal of **NoAW** project is to generate innovative efficient approaches to convert growing agricultural waste issues into eco-efficient bio-based products opportunities with direct benefits for both environment, economy and EU consumer. The project plans to develop innovative eco-design and hybrid assessment tools of circular agro-waste management strategies and address related gap of knowledge and data. The project develops breakthrough knowledge on agro-waste molecular complexity and heterogeneity in order to upgrade the most widespread mature conversion technology (anaerobic digestion) and to synergistically eco-design robust cascading processes to fully convert agro-waste into a set of high added value bio-energy, bio-fertilizers and bio-chemicals and building blocks.

The **OPTIFUEL** project developed a smart, reliable and fully-automated solution, which provides reliable real-time data on biofuel quality. Fuel quality is monitored at one or more critical stages of the fuel handling chain. This data is passed to a control room, where the fuel management system is used to optimise the sorting, storing, mixing and feeding of biofuel, and the precise combustion in the boiler. The OPTIFUEL interface is also integrated into the control and fuel management systems of power plants, to optimise energy production across the entire biofuel process. The team installed and demonstrated the system in the field and carried out successful demonstrations of the system, receiving positive feedback.

The **PELLETON** project aimed to assess the technical feasibility as well as economic viability of the implementation on the EU market of a device for production of pellets from biomass and agricultural waste for energy purposes. The solution is now at the TRL 6 being was demonstrated and tested in a relevant environment. This device is a mobile pellet production line for manufacturing pellets from biomass and agricultural wastes involving pre-fragmentation and cleaning of biomass, having the ability to process hardly manageable bio-sewer sludges, avoiding the processes of drying and grinding of biomass. One of the main technological challenges were to design and develop a control system of the automatic system, allowing flexible operation with the use of appropriate sensors, controllers and inverters.

The core part of the **progRESsHEAT** project was the communication and capacity building process with policy makers, administrative staff and other stakeholders at the local, regional and national level. The project worked with decision-makers to draw up recommendations for a raft of policies to encourage sustainable solutions. It provided an analytical basis for policy development in the field, including an assessment of cross-sectoral effects between renewables and energy efficiency measures in industrial heating and cooling, excess heat, heating and cooling in buildings, and district heating. Heating and cooling strategies were developed based on in-depth analysis of the local authorities' specific circumstances, including barriers and drivers, and a model-based assessment of policy intervention in scenarios up to 2050. The EnergyPRO local energy advisory tool together with the newly developed Least-Cost-Tool was used for local case studies to appropriately reflect district and individual heating and cooling demand and supply.

The primary objective of the **Prometheus-5** project was the development of a decentralized (on or off grid) H2PS-5 micro-CHP system to convert the fuel (LPG/NG/Biogas) into electrical and thermal power through a PEM fuel cell, with intermediate production of H_2. The system is fuel flexible, operating with natural gas, propane/liquefied petroleum gas (LPG) or biogas with a nominal capacity of 5 kWe and 7 kW of thermal energy and electrical efficiency above 35%. The reformer sub-assembly and CO minimization sub-assembly have been constructed and then tested for validating their performance. In addition the power electronics have been integrated with the fuel cell stack resulting in a power production system and tested for validating its performance.

The **Proxipel** project proposes an innovative solution consisting in a mobile pelletizing unit, placed on a trailer that can be connected to a normal truck for transportation. This eliminates associated costs with buying land and obtaining building and permissions. The raw material is crushed, milled, dried, and pressed to biopellets. This solution can handle a large variety of raw material, like straw, nut shell, rice husk, etc., although the main raw material is expected to be wooden residues.

The **REGATRACE** project will create an efficient trade system based on issuing and trading biomethane/renewable gases Guarantees of Origin (GoO) along with cost-effective logistics. Biomethane/renewable gases can be produced from waste or residual streams of organic material and they can be transmitted and stored in existing infrastructures, so allowing to combine the European natural gas and electricity grids. According to the project, a Europe-wide trade centre for biomethane (and other renewable gases) is necessary for enabling investments and promoting cross-border biomethane trade. This objective will be achieved through setting up of a European biomethane/renewable gases GoO system, set-up of national GoO issuing bodies and the integration of GoO from different renewable gas technologies, with electric and hydrogen GoO systems.

The **Res2Pel** project aimed to present an overview of the methodology used to identify wet biomass waste streams in order to find potential markets for the promotion of the eco-innovative, resource-efficient treatment process for the biomass residues from agriculture or landscaping, reducing water content, harmful substances and inert material in the biomass fractions to produce a high-grade biomass fuel. The waste streams/categories that are organic or partly organic and therefore potential input streams for the florafuel treatment plant were defined and assessed. The biomass was characterised to evaluate its suitability for the treatment process and to describe the change in the composition of the solid fuel after the treatment process. The feasibility study aimed to reveal the technical feasibility and the optimal way to reduce the manufacturing costs fostering its market uptake. A business plan will be developed for commercialization.

The **ROBIOT** project addressed an automated solution that renews the raw material quality management at biomass power plants and biorefineries that enables a completely new level of intelligent biomass quality management across the whole supply chain. The aim of this study was to develop a sustainable plan for scaling up the business for creating a thorough understanding of the market and customer needs, scouting for partners and business development based on the market analysis. It performed a comprehensive market analysis (market potential, target customers, potential partners, local sampling and quality management practices, competitors) in selected countries.

The **SecureChain** focused on promoting the market uptake of bioenergy in six European model regions with the objective to promote a Sustainable Supply Chain Management (SSCM) practice that meets the highest environmental quality and financial viability standards. The team cooperated with regional companies to promote sustainable bioenergy supply chains in six selected model rural regions in Europe, the pilot projects that covered the entire bioenergy supply chain, from biomass harvesting and fuel production to energy conversion and recycling. The project improved the know-how, international positioning and mutual outreach of the selected model regions. The demonstrated solutions from the successful pilot projects help boost competitiveness and sustainability of bioenergy, and also serve as recommendable, transferable practices for other regions.

The **SEEMLA** project set out to establish suitable innovative land use strategies for sustainable production of plant-based energy on marginal lands (MagLs) while improving general ecosystem services and sustainable exploitation of biomass from MagLs that are not used for food or feed production and do not pose an environmental threat. SEEMLA applied an approach consisting of an integrated set of biophysical criteria to define land marginality and assess their potential for biomass production for bioenergy that was tested in several areas. The project assessed the availability and suitability of MagLs as alternative production sites for renewable resources and evaluated the degree of marginality using the Muencheberg soil quality rating (SQR tool) to assess soil fertility as a key factor in determining marginality. This method led to the development of a geographic information system (GIS) tool that maps MagLs across Europe.

SE-SBR proposes a novel BECCS technology, sorbent-enhanced steam biomass reforming (SE-SBR), where bio-energy conversion is integrated with carbon capture. To fulfil this technology, a bifunctional sorbent-catalyst material (BSCM) will be designed and tested and the fundamental component interactions in nanoscale in the material will be explored. The proposed SE-SBR with BSCMs is expected to replace the conventional biomass conversion methods, ease the fossil fuel energy crisis, and contribute to the low carbon world.

The focus of this **SmartGasGrid** study is to analyse the technical adaptions required for the optimization of renewable gas injection, build a demonstrator and evaluate go-to-market and pricing options. A novel, cost-effective smart grid technology has been developed to monitor and control gas pressure, flow & gas quality by means of cloud-based, algorithm-driven hardware that can be easily installed without the need for any changes in the gas infrastructure. A pressure management application helps utilities reduce gas leakage to TRL 6.

The **SolBio-Rev** project will develop a flexible energy system suitable for building integration based on renewables for covering a large share of energy demand (heating/cooling/electricity). The overall objective is to develop a configuration based on renewables that allows covering all heating and cooling demand and a variable electricity demand in a cost-effective manner. This configuration is based on solar, ambient heat and bioenergy, while it is suitable to be installed in various buildings types and sizes. The SolBio-Rev concept is based on solar thermal collectors with vacuum tubes combined with thermoelectrics, a cascade thermal chiller with electrical-driven heat pump, a reversible heat pump/ORC for enhancing flexibility and switching operating modes between summer and winter, exploiting all available solar heat, and an advanced biomass boiler coupled with the above ORC for CHP operation. A smart control is also envisaged to manage and optimise the system operation with user-friendly features.

The project **STORE&GO** will demonstrate three “innovative Power to Gas storage concepts” at locations in Germany, Switzerland and Italy in order to overcome technical, economic, social and legal barriers. The demonstration will pave the way for an integration of PtG storage into flexible energy supply and distribution systems with a high share of renewable energy. Using methanation processes as bridging technologies, it will demonstrate and investigate in which way these innovative PtG concepts will be able to solve the main problems of renewable energies: fluctuating production of renewable energies; consideration of renewables as suboptimal power grid infrastructure; expensive; missing storage solutions for renewable power.

The project **uP_running** has been established to unlock the potential of biomass from agrarian pruning and plantation removal (APPR), especially those obtained from vineyards, olive groves and fruit tree plantations. The project has implemented a series of actions to counter the misconception in the agricultural and energy sectors that this type of woody residue has little or no value. A major activity was the organisation of 20 demonstrations of APPR biomass value chain operations that were performed by the agrarian and technical partners who have helped new entrepreneurs interested in initiating value chains draft appropriate business models, overcome technical issues related to harvesting equipment and check the sustainability of their value chains. It has caused new value chains to settle, new initiatives to start, created permanent capacity in several countries.

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 55 projects have been identified as addressing the research on anaerobic digestion and biogas production under H2020 RTD EU programme.

The **ABWET** (Advanced Biological Waste-to-Energy Technologies) European Joint Doctorate (EJD) program provided education and research at PhD level on environmental technologies that convert waste materials into bioenergy, training Early Stage Researchers (ESRs) to work in multidisciplinary teams. The ABWET EJD focused on fundamental and applied aspects of different treatment technologies of waste, with a focus on anaerobic treatment processes, valorisation of the digestate and biofuel clean-up, as well as the development of innovative recovery technologies with high market potential. This makes the ABWET PhD alumni attractive scientists and engineers for European universities and companies, able to contribute to the global challenges of waste management, energy scarcity and sustainable development. The ABWET EJD developed a joint PhD education and research curriculum with joint selection, supervision and PhD defense procedures in order to issue a fully joint PhD degree in Environmental Technology.

The **ADD-ON** 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 project focuses on scaling up the current pilot equipment into industrial scale (over 1000 m3 of biogas production reactor), optimization of the process, and convincing reference customers to enable broader market penetration. The pilot scale tests demonstrated the long term operation of a biogas plant using high nitrogen feedstock for biogas. The market research verifed the market potential of the technology within the within the European ans US biogas market.

The **AMBIENCE** project investigated a revolutionary approach for the effective capture of ammonia from farm and biogas plants. The system transforms the ammonia to give ammonia sulphate, a valuable product for manufacturing fertilisers and related products. Researchers developed a novel highly efficient, low-cost, closed-loop system based on permeable membranes that capture 70-80% of ammonia emissions generated from animal waste and biogas plant digestants. AMBIENCE provides a new modular portable treatment plant, which allows farmers to capture and valorise ammonia and increasing incomes by more than 10%. The project also accelerated the uptake and international penetration of AMBIENCE by conducting a market feasibility analysis, with a particular focus on validating the target market and its size. Researchers also carried out a study of competitors, an analysis of customers and their willingness to pay, and defined the product value chain. In addition, a technical roadmap was developed for a feasible industrial scalable solution.

The **ANAERGY** project has developed a novel modulable treatment system that integrates anaerobic, aerobic and advanced oxidation stages. The anaerobic digester, including patented PUREMUST® technology, can reach high pollutants' elimination rates (up to 99%) along with production of biogas (16 m^3/h). The industrial adoption of the ANAERGY system can result in major economic savings, while decreasing water pollution, increasing water reusability and boosting renewable energy share. Its small size and flexibility allow reducing installation and operational costs, together with a tailored response to end-user´s requirements. The system tackles the issues of the heterogeneity and seasonality of the agro-food sector that produce a broad variety of wastewater streams which claim for more efficient and customizable solutions to meet with increasingly stringent wastewater regulations.

This **AnBIOSST** project aimed to obtain essential knowledge about anaerobic bioleaching (ABL) as sewage sludge treatment resulting from wastewater treatment, and the effect of ABL on the efficiency of subsequent anaerobic digestion. Anaerobic digestion (AD) of sewage sludge from wastewater treatment, is widely applied, resulting in volume reduction and biogas production. However, high heavy metal contents in sewage sludge impede the use of raw sewage sludge or AD effluent to be used as fertilizer. Because of its potential to remove heavy metal from solid matrices, bioleaching has been considered as a promising technique for both raw sewage sludge and anaerobic digestion AD effluent. The application of anaerobic bioleaching to sewage sludge prior to anaerobic digestion increases the bio-availability of HM (which serve as micronutrients to AD microorganisms), produces volatile fatty acids (VFA), (AD intermediates); and (iii) the sludge is already in a reduced state before in enters the digesters.

The project **Bin2Grid** promoted the segregated collection of food waste, its conversion to biogas and upgraded into biomethane for supplying local fuelling stations in several cities and help make biomethane a more sustainable alternative to fossil fuels. Two key sectors were specifically targeted: waste management and renewable energy production, with the aim of bridging existing gaps between the two. The consortium analysed existing technologies related to biowaste separation and treatment, biogas production and upgrade, as well as biomethane utilization. Then, the project investigated possible economic tools to increase the profitability of the proposed concept. The project developed an Excel-based benchmark tool which compares organic waste in the biomethane value chain with other waste treatment value chains such as landfilling, composting and incineration that was already applied to several cities. The biomethane tool can be used to estimate investment, operating and initial of costs of different facilities for biogas production, gas upgrading and utilisations of biomethane.

BIOFERLUDAN 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. A biogas plant which use BIOFERLUDAN process will produce a minimum of 60L of fertilizer per ton of digestate. BIOFERLUDAN completed the feasibility atudy, to secure IPR and ensure free BIOFERLUDAN operation, to detail primary (biogas) and secondary (fertilizers) markets, to specify commercialization channels and commercialization scenarios and to quantify the business plan and financial/exploitation figures.

Biofrigas project is based on a developed and piloted an effective, decentralised, small-scale, containerized energy plant that converts manure into 97% pure liquefied biogas and separates the CO_2 it contains. It targeted a commercially viable technology that can generate liquid biogas at a small scale, without the need to collect and transport the bulky manure to a centralized plant and to install container based liquefied biogas plants on agricultural sites and then sell the produced fuel to LBG distributors. The project completed the assessment of the technical feasibility and business opportunity, identifying the needs and demands of farmers and other stakeholders, additional functionalities that farmers are looking for and the best business model to exploit the technology. This feasibility study performed the gap analysis, cost analysis on the current business case (CAPEX OPEX), lifetime maintenance costs analysis, scale up analysis, business model analysis for different potential business models.

The **BioFuel Fab** proposes an energy self-sustainable and versatile solution able to make biogas production from lignocellulosic wastes economically profitable and environmentally sustainable. This is achieved thanks to a proprietary high-temperature and high-pressure pretreatment process that makes woody waste suitable for anaerobic digestion. The digestion process speed is increased up to 75%, empowering the AD plant capacity by 3 times. The innovation allows to reach a profitability of biogas production from lignocellulosic waste material to be comparable with energy crops and makes convenient to convert the existing biogas plants using energy crops as feedstock to a BioFuel Fab fed by woody wastes, with a payback for the investment of 2.5 years.

The **Biogas2Syngas** project addresses the production of biogas and dry reforming of methane (DRM) into syngas. Despite the significant potential, DRM has not been commercialized due to catalyst instability leading high operational cost. Knowledge of structural/morphological changes of catalyst under reaction conditions is important for rational design. To address these issues, concepts based on combined experiment and theory are proposed. Understanding catalyst structure-activity relationship, and mechanistic insights into the DRM process will be developed through operando Raman experiments and Density Functional Theory (DFT) calculations. Multiscale kinetic modeling will be executed for rationalize experimental trends and establish catalyst structure-activity relationship that will provide an insight about the effective catalyst design and offer an avenue to explore new concepts and opportunities for industrial catalysis development.

The **BiogasAction** goal has been to support the development of the European biogas/biomethane sector and thereby contribute to the EU 2020 targets by focusing on removing non-technical barriers to widespread production of biogas from manure and other waste. BiogasAction has compiled comprehensive tools and guidelines aiming to achieve the project's ambition of an unbiased and rapid regional development of the European biogas/biomethane sector. An interactive database has been developed, including description and evaluation of general supportive documents, boundary conditions in particular regions and projects, analysis of target audience for particular measures. The data has been processed to provide user-friendly filtering system and data base for online data research.

BIOGASTIGER developed 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. The components of BIOGASTIGER system have been analyzed, optimized and designed. The concept of separation unit for digestate has been analyzed, optimized and tested in field. Production methods have been planned, Tools for partly-automated assembly of BIOGASTIGER components have been developed. A web-based layout tool to determine the size and selection of technological components for individual customers has been developed and brought online.

The **BIOGRAPHENE** project focussed on a developed a plug-and-play solution for producing graphene from biomethane in biogas plants via Chemical Vapor Deposition (CVD) based on a prototype of the technology (now TRL 6). In the agri-food industry and wastewater treatment plants, anaerobic digestion is a proven technology for treatment of wet-waste biomass, which allows generation of biogas as renewable energy. Additionally, biogas can be upgraded into biomethane and CO_2, which are organic carbon sources which can be used as raw materials for manufacturing biographene. Installing a Biographene Production Unit with biogas plants will allow graphene production to be economically viable at industrial scale and is a way to increase the profitability of biogas plants and boost the renewable energy sector.

The project **bionic agitator** addressed a prototype of a newly developed with potential for energy reduction in agitator technology. The prototype of the **bionic agitator** has shown the potential to reduce this energy consumption by 60% or more. As a result of this increase in the effective output it becomes more attractive to generate energy from organic waste. The bionic agitator feasibility study was performed to obtain reliable data on the energy reduction, the material used and to get a solid feedback from potential customers. The proposed feasibility study includes a field test where the bionic agitator was installed in five existing biogas plants to test it against a conventional agitator.

BIONICO had the goal of developing, building and demonstrating at a real biogas plant (TRL 6) a fuel reformer for direct biogas conversion to hydrogen and demonstrate the new reformer using a novel catalytic membrane reactor in a single step. The biogas-to-hydrogen plants were simulated in Aspen Plus and their performance were assessed with efficiencies around 59% for steam reforming based concept. A range of novel reforming catalysts have been developed for the biogas composition identified in the project. Porous supports, palladium based membranes and sealings have been developed for hydrogen separation in biogas reforming fluidized bed membrane reactor. Stability and performance of the catalyst and membrane where assessed in fluidized bed conditions. The system lay-out was defined and its performance assessed with ASPEN plus flowsheet models using two different biogas compositions and two different permeate side conditions showing sfficiencies above 72% for several operating conditions.

The **BIOO** project exploits the Plant-Microbial Fuel Cell (PMFC), which is characterised by the fact that the generation of such electricity is done by means of anaerobic bacteriological synthesis of the organic matter produced during plants' photosynthesis producing green electricity for residential use. The project carried out the technical and commercial activities required to obtain a marketable and ready to certify BIOO Panel system, as well as to create a demonstrative platform.

The goal of **BioRECO2VER** is to 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 valuable platform chemicals. The project focuses on minimizing gas pre-treatment costs, maximizing gas transfer in bioreactors, preventing product inhibition, minimizing product recovery costs, reducing footprint and improving scalability. A hybrid enzymatic process is being investigated for CO_2 capture from industrial point sources and conversion of captured CO_2 into the targeted end-products will be realized through three different proprietary microbial platforms. Bioprocess development and optimization will occur along fermentation and bioelectrochemical systems. The most promising solution for each target product will be validated at TRL 5.

The **BIORELOAD** project addressed a biological technology for the pre-treatment of lignocellulosic material which allows increasing its degradability and the biogas yield by up to 50% using selected bacteria strains and fungi. It will allow biogas plant operators reducing feedstock input and thus related costs and revalorising certain waste streams for energy production. Further testing under different operational real-scale conditions and with different substrates are necessary during a demonstration stage prior to commercialisation. The project carried out a feasibility assessment, leading to a roadmap for the further technical development and industrialization of BIORELOAD, and a business plan.

BioROBURplus addresses the development of a pre-commercial fuel processor (direct biogas oxidative steam reformer) delivering 50 Nm^3/h H_2 from biogas from landfill gas, anaerobic digestion of organic waste, or wastewater-treatment sludge. The energy efficiency of biogas conversion into H_2 will exceed 80%. The process is based on increased internal heat recovery, a tailored pressure-temperature-swing adsorption (PTSA) and a recuperative burner capable of exploiting the low enthalpy gas to provide heat. BioROBUR developed advanced modulating air-steam feed control system for coke growth control, a catalytic trap hosting WGS functionality and allowing decomposition of incomplete reforming products.

Biowave developed an innovative microwave pre-treatment technique that increases the compatibility of pig slurry for anaerobic digestion. Additionally, the system has great potential for enhancing biogas production from other typical feedstocks such as energy crops, cattle slurry and food waste. The biowave process converts the hard carbon in the feedstock which bacteria cannot digest, into soluble carbon, thus improving the Carbon:Nitrogen ratio and so also the total bio-available carbon for anaerobic digestion. Organic material is pumped to the system and microwave energy disrupts the cell structure within the material making it significantly more digestible – resulting in higher biogas yields and faster anaerobic digestion. Removing the necessity to add organic material increases the biogas yield from slurry by over 40%, offering farmers a means to utilize ever-growing amounts of slurry.

The project **BPV** addressed a customizable rendering process to valorise slaughterhouse waste in such a way that animal byproducts (ABP) are converted into fuel for biogas generation through anaerobic digestion. The BPV process entails the avoidance of several typical stages to separate proteins from the mix, and thus reducing costs. The outputs of the process, the BPV-products, are excellent fuel for biogas generation, with large methane generation potential, as is proven by the high methane content reachable by the raw biogas obtained from the BPV-products (up to 70% CH4 content). BPV aimed to commercialize the technology: ultimate the design of commercial plants, build and test pilot installations, adjust the technology, industrialize the production, protect IPR and close agreements with stakeholders required for the commercialization.

The **CoMeth** project proposed a commercial methanation technology for any source of CO_2 gas which allows the conversion of surplus power into a grid compatible gas without complex gas conditioning. CoMeth offers the disruptive technology that scales up the process of methanation for any CO_2/CO source through a cutting-edge fluidized bed reactor containing nickel as catalyst, providing current providers of CH_4 to the grid (Waste Water Treatment Plants and fermentation plants) considerable growth of production yield up to 60% from the same amount of biomass substrate and avoiding the CO_2 removal cost. Methanation processes (converting CO_2 into methane) are key enabling technologies because the output of the operation can be stored and transported through the natural gas transport infrastructure.

The **DECISIVE** project offers to demonstrate the ability to decrease the generation of urban waste flows and increase recycling and recovery by focusing efforts on decentralised management and valorization of the biowaste, through anaerobic digestion (AD) and solid-state fermentation (SSF). To reach this objective, the project targets two major advances. The first one is an organizational advance with the proposal of a new management strategy for urban biowaste (DECISIVE system), based on local micro-scale systems and circular thinking for valorization, forming the ground-breaking concept of network of urban decentralised valorization sites. The second one concerns technologies with the development of eco-efficient micro-scale biological processes: micro-anaerobic digestion (mAD) and solid-state fermentation (SSF). An overview of the available mAD process for biowaste treatment and of technical, regulatory and social aspects has been provided. Moreover theoretical estimations of biowaste amounts to ensure the energy self-sufficiency of the micro-AD unit were performed. The results showed that the micro-AD scheme developed should be able to treat at least 50 t/year and that a solid state anaerobic digestion was the most attractive technology to set up as new biowaste treatment.

The objective of **DEMETER** was to increase the yield of this industrial fermentation process through the use of nely developed enzyme, improve the product recovery process, and reduce overall product cost while increasing the productivity of the process. An improved fermentation process for enzyme production at lab-scale was developed for scale-up to pilot level and first runs at industrial scale. The results have also been used to develop a mathematical model based on all the different variables and parameters present in the fermentation process. The model was used to improve fermentation protocol further to get a more efficient enzyme production process. The improved fermentation process showed an improved yield in 1500L scale fermenters: 35% more protein has been produced. The team has also compared different strategies to optimize the downstream process for enzymes purification.

DEMOSOFC aims at demonstrating a medium-scale distributed CHP system (electric power of 175 kW) based on SOFC and fed with locally available biogas produced in a waste water treatment plant. The objective is demonstration and in-deep analysis of an innovative solution for distributed CHP generation based on SOFC, for a sub-MW distributed CHP. DEMOSOFC has built a demo plant of 174 kWe (+ 89 kWth) fed by biogas from wastewater treatment plant WWTP aiming at the integration of a fuel cell power plant in a real industrial site, i.e. the wastewater treatment plant providing biogas to the SOFC. Operation of the demo plant was organised for data collection and analysis to prove the performances of such systems: electrical efficiency, thermal recovery, emissions and plant integration.

The project **DIET** proposes an advanced anaerobic digestion technology by introducing conductive materials (such as biocompatible graphene nanomaterial and digestate derived pyrochar) for gaseous biofuel production from algae feedstock. The proposal will particularly explore the mechanism of efficient direct interspecies electron transfer (DIET) between bacteria and methanogens in the presence of conductive materials. The biomethane production rate and total energy recovery in the proposed system are expected to be enhanced by 20-40% as compared to existing anaerobic digestion technology. Anaerobic digestion is being widely applied to produce biogas through complex communities of syntrophic bacteria and methanogenic archaea. However, it can suffer from the inefficiency of biogas production, which fundamentally arises from the low efficiency of mediated interspecies electron transfer via hydrogen between bacteria and archaea.

The aim of the **DualMetha** project was to improve the understanding of the EU market for biogas, identifying regional market variations in terms of purchase decision makers, appropriate business models, pricing structure and identifying which are the most attractive markets for us to use as a beachhead. This is based on a developed and patented a simplified, biomethane production process that reduces the waste pre-treatment stages, allows for the methanation of all types of biomass including straw and has low OPEX (50% less in maintenance, repairs and electricity costs). DualMetha represents the opportunity to turn unexploited organic waste into biogas.

FimusKraft has developed an innovative 3-step bio-fermentation process that uses enzymes to optimise the Methane to Carbon Dioxide ratio of the bio-waste before the feedstock enters the fermenter. The system is the first combining bio-gas fermenting with the pre-handling of the bio-waste through enzymes. This ensures biowaste fermentation into biogas to produce heat, fuel and fertilizer from organic resources.

The **FlexBio** project addressed a standardized, modular and high capacity wastewater treatment plant that can be adapted to nearly any requirement, based on a combination of anaerobic technology and aerobic membrane bioreactors. Organic contaminants in the wastewater are converted into biogas under anaerobic conditions in a fixed-bed reactor. An optional second treatment step, a trickling filter, can moreover remove nitrogen compounds and further increase the treatment efficiency of the plant. The project framework analyzed existing markets and identified new markets. The feasibility of the finalisation and market introduction of the FLEXBIO wastewater treatment plant was assessed. A concept of a container-based prototype for further tests and demonstrations at potential customers was developed.

The **GASFARM** project addressed a small-size anaerobic digester based on Anaerobic Baffled Reactor technology. GASFARM will be used by small and medium farms from livestock and agricultural industry. GASFARM is a multi-chamber reactor that allows a longitudinal separation and distribution of the different reactions (hydrolysis, acidogenesis and methanogenesis) that occur during biogasification. This reactor improves the hydrolysis, acidogenic, acetogenic and methanogenic yield, protects against toxic materials and provide higher resistance to changes in operational parameters, making AD technology ideally suitable for small and medium farms. The project completed a feasibility study, assessing the technical, commercial and financial viability of the solution and revenues, costs, pricing, margins and payback.

The overall aim of the **H2AD-aFDPI** project was 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 conventional anaerobic digestion (AD) (TRL 6/7). H2AD is based on a patented bioreactor and electrode architecture. The core technology is an integrated and closed loop microbial fuel cell, based on a novel hybrid of traditional anaerobic digestion and conventional MFC technology. H2AD-aFDPI aimed 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. The project built H2AD units for the pre and post treatment of organic waste at five sites. The five trial sites were successfully installed and commissioned to deliver successful trials and solid results that prove the technologies effectiveness, reliability and adaptability.

HOMEBIOGAS develops and markets advanced biogas systems that reduce waste management fees, energy cost and environmental footprint by converting organic waste to biogas. HOMEBIOGAS develops and markets advanced biogas systems converting organic waste into biogas, based on an existing advanced, cost-effective household biogas system. The project aims to offer an affordable, 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. HOMEBIOGAS TG6 has been demonstrated at TRL 6 through the development and trial of two large (200-250 kg per day) pilots. The project developed, installed and operated the first pilot system followed by a second pilot, with an improved design.

The **INCOVER** project proposed new wastewater treatment solutions producing new added-value bio-products - chemicals, irrigation water and bio-fertiliser using innovative monitoring methodologies and a Decision Support System (DSS). Furthermore, upgraded methane, CO2 and bio-coal are extracted to reach at least a 50% reduction of the energy and raw material demand. The consortium has already tested INCOVER technologies at lab/pilot scale (TRL 4-6) and INCOVER plants will be implemented at demo scale to achieve TRL of 7-8. The INCOVER plants will generate benefits from wastewater through: 1) chemical recovery (bio-plastic and organic acids) via algae/bacteria and yeast biotechnology; 2) near-zero-energy plant providing upgraded bio-methane via pre-treatment and anaerobic co-digestion; 3) Bio-production and reclaimed water via adsorption, biotechnology based on wetlands systems and hydrothermal carbonisation.

The **KATEDRAL** project performed a feasibility study on an innovative technology for waste management of sewage sludge turning it into valuable by-products and energy such as biogas, clean water and natural fertilizers that would otherwise be lost during disposal process. Sewage sludge management constitutes high costs for a wastewater treatment plant (WWTP), one third of the total capital expenditures (CAPEX) and up to 50% of the operational costs (OPEX). The treatment unit KATEDRAL that can operate with the vast majority of liquid waste streams, and contribute to provide a cost-efficient, ecological and reliable disposal solution.

The **KUDURA** project proposed a disruptive portable solution for waste - to -energy and water treatment, which operates off-grid, which use transforms cow and pig manure waste into biogas to feed a combined heat and power plant to obtain electricity and heat. Furthermore, agricultural waste-water can be treated with the same solution contenereaized solution. The project carried out various analyses concerning a technical development assessment and deep market study, including analyses about the global market size and the European rural dairy and pig markets' status quo.

The **Lt-AD** project proposed a novel low-temperature Anaerobic Digestion (below 20 °C) 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. The technologies currently employed for low temperature, low strength wastewater treatment are Aerobic Activated Sludge treatment or Membrane Bio-reactor treatment. This solution offers reduced OPEX expenditure on wastewater through reducing the chemical oxygen demand (COD) and total suspended solids (TSS) concentrations in their effluent with minimum operating costs and utilising a usable, revenue generating, biogas by-product.

The **MUBIC** project aimed at developing a new concept for biogas production, mushroom production and energy and nutrient recovery. It proposes an innovative method to produce a new substrate that enables optimal recovery of nutrients and provides highly efficient use of biomass at low cost. The Advanced Substrate Technology (AST) solution will contribute significantly to the efficiency of biogas. The project aimed at establishment of an Advanced Substrate Technology plant in commercial scale as add-on to a biogas plant in commercial scale and validate the feasibility and the reduction in production cost of substrate for mushroom production. The layout plans have been updated for the main technologies and components as part of add-on facilities to existing biogas plants. Specification on selected key technologies has been elaborated, and some of the technologies have been put in production and their capacity have been tested to obtain important updated data on function, performance and efficiency.

The **Multi-AD** carried out the activities needed to verify the viability of upscaling and bringing Multi-AD system to the market (from TRL 6 to TRL9). Multi-AD is a high performance MULTIphase Anaerobic Digester (TRL 6 level) tailor-made for treating wastewater generated in Food and Drink SMEs. It is fitted with advanced control system that will be integrated to fully automate the process, to self-regulate basic operational parameters depending on the kind of wastewater characteristics it needs to treat. It will generate 80% methane-rich biogas that be partially used -50%- for its operation, and partially used -for other energy-demanding industrial tasks (e.g. heating), with average economic savings of 15,000€/year (when treating 100 m^3/d) and 11% less CO_2 emissions. The system applies to different reactor volumes (from 25 to 500 m^3). The manufacturing and industrial distribution of Multi-AD have also been evaluated and defined depending on the customer´s location and the size of the anaerobic reactor.

The project **NOMAD** aims to develop an innovative, small-scale tech solution designed to recover fibre and specific nutrients from digestate for formulation into high performance bio-fertiliser products. The proposed technology will utilise heat from combustion of waste timber and recovered energy from a collection vehicle to improve energy efficiency while simultaneously addressing regulatory compliance. Specific nutrients will be extracted from the liquid fraction and water recovered for reuse. The remaining sludge will be blended & composted with ash (derived from waste timber combustion) and biochar to produce optimised, nutrient-balanced soil conditioners. The model rests on the solution's mobility and modularity as one unit could serve multiple plants, tackling digestate from a range of feedstocks with shared costs making it more viable than installing systems at individual plants.

The **NTPLEASURE** project aimed to develop an integrated separation-nonthermal plasma (NTP)-catalyst system to enable the biogas utilization. The system is based on selective capture of CO_2 from biogas with ultra-thin SAPO-34 zeolite membranes and subsequent NTP-assisted catalytic CO_2 methanation on Ni- and/or Co-based catalysts supported on 5A zeolite membrane. The design combines CO_2 capture and methanation at ambient temperature for industrial scale biogas upgrade process. This project uses transient kinetics and advanced in-situ characterization methods to understand the reaction mechanism and nature of the active site, including steady-state isotope kinetic analysis, short-time-on-stream diffuse reflectance infra spectroscopy and near ambient pressure X-ray photoelectron spectroscopy, etc.

The **OptiMADMix** project aimed to deliver a methodology to improve mesophilic anaerobic digestion design and control, reducing energy consumption and maximising biogas production. It provides a numerical framework to optimize the digester performance. The complex relationships between hydrodynamic and microbiological processes were 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 methodology improves MAD design and control, leading to improved performance that reduces operating costs and improves the financial performance of the mesophilic anaerobic digester.

The **PHARM AD** project investigated the application of anaerobic digestion for the removal of pharmaceutical residues from wastewater 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). The project also investibaged pharmaceutical residues removal by anaerobic digestion with biological nutrient removal (nitrogen) by micro-algae cultivation thus addressing one of the drawbacks of AD: the lack of nitrogen removal. Tests were carried out by the design of a laboratory scale anaerobic digestion process to evaluate the long term effect of pharmaceutical residues in the system. The experimental results concluded that the presence of high pharmaceutical residues concentrations in wastewater may inhibit the anaerobic process and biogas production. The tests on the use of algae proved to be an an attractive and efficient option for recovering nutrients

The project **Poul-AR** proposes an integrated biological approach for the pre-treatment and valorisation of poultry manure. The liberation and fixation of nitrogen as nutrient is optimized and the product consists of a valuable ammonium salt directly applicable as fertilizer.The project performed a feasibility check of the Poul-AR solution including a proof of technology, an optimization of separate technological processes at lab- and pilot scale, a business case determination of the system and a market study allowint Poul-AR to reach TRL 6. During lab- and pilot tests the optimization of mixing, heating, stripping air amount and chemical aid amount resulted in nitrogen removal ratios of up to 95%. These results were used for potential business cases for installation of variable size and resulted in the compilation of a reliable modelling tool for the calculation of operational costs, benefits, investment and inputs and outputs of the system.

The project **POWERSTEP** aimed to demonstrate innovative concepts at full scale to design energy positive wastewater treatment plants. The realisation of an energy-positive wastewater treatment plants requires a combination of new concepts for wastewater treatment together with an optimised integration of existing technologies in all side aspects, including sludge treatment and biogas valorisation. POWERSTEP uses concepts and technologies that have been tested in laboratories and pilot scale plants. The project investigated enhanced carbon extraction (pre-filtration), innovative nitrogen removal processes (such as advanced control, main-stream deammonification, duckweed reactor), power-to-gas (biogas upgrades) with a smart grid approach, heat-to-power concepts (thermoelectric recovery in combined heat and power units, steam rankine cycle, heat storage concepts) and innovative process water treatment (nitritation, membrane ammonia stripping).

The **Record Biomap** had the objective to establish the most promising innovative process and technology solutions along the biomethane supply chain, from raw material/residues, substrate pre-treatment, digestion, gas conditioning/digestate further utilisation and digestate/fertilizer deployment for a cost and energy sufficient biomethane production and to support their development up to market uptake. The project provided a comprehensive overview and multi-indicator assessment of European small-scale, innovative technologies for biomethane production. Technical, economic and ecological indicators for small-scale biomethane technologies (with low TRL) were defined, applied, and compared to larger scale references. The project also provided an overview of financial and regulatory framework conditions for biomethane and biogas in Europe. The project created the Biomethane Map, an interactive online map giving an overview of innovative technology solutions for small-medium scale biomethane production across the biomethane supply chain.

The **RGH2 OSOD system** project proposed to develop a compact on-site on-demand (OSOD) hydrogen generator based on a ground-breaking one-step process technology. It combines a hydrogen generator and storage device in a single unit, allowing for the local delivery of hydrogen. The device utilises hydrocarbons such as biogas, biomass or natural gas, which are heated and mixed with steam to generate hydrogen at extremely high purity, requiring no additional purification procedures. The compact on-site on-demand (OSOD) hydrogen generator system allows biogas to be converted into H2 and the storage of already produced H_2. The Technical and financial studies were finished concluding that there is a solid business opportunity for the OSOD system in various industrial fields today already.

The **SHEPHERD** project aimed to improve an existing prototype of on-line microbial respiro-meter for monitoring the activity of the microbial population in activated sludge for wastewater applications (TRL 6 to TRL 8). It aimed to develop a Monitoring and Management System (Shepherd), including a combination of novel hardware, a fully integrated software system, local interface and cloud based dashboard, to enable the reduction of electricity usage and carbon emissions, while providing operators with plant performance information, and alerts for process failures. An improved SHEPHERD prototype has been developed, with upgrades relating to sensing capabilities (new biomass probe), updated analogue and digital outputs (supporting closed-loop systems), integration connectors (supporting most common SCADA systems) and secure cloud connection.

The **SYSTEMIC** 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. Within the project demonstration plants will demonstrate new approaches for the valorisation of biowaste into green energy, mineral resources, fertilizers and organic soil improvers. This allows innovative combinations of modules to elaborate possible optimizations for increasing the production quantity and quality of new products. Existing biogas plants will be enhanced with novel nutrient recovery technologies. The demonstration plants made significant effort to realise novel proven technologies at their site (TRL 7-8 Level) in order to become leading pioneers and showcase nutrient recovery at large scale.

UBI proposed a simple, cost effective biogas upgrading technology, based on biological processes, and specifically designed for small scale. It reduces energy requirements and operating costs. In addition, it captures and stores the CO_2 removed from the biogas in the form of biomass, which is readily available for new biogas generation. UBI holds the potential to disrupt de-localized biomethane production making it economically feasible in scenarios where it is not considered an option nowadays. The project carried out a solid feasibility study covering all the aspects required prior to market launch: detailed analysis of the technical development needed, in-depth commercial feasibility study including a detailed market assessment; and a thorough financial plan covering all the following stages.

UltraBio project addressed a new procedure for the treatment of manure, digestate and other organic suspensions which not only enables their disposal but also their valorisation. The substances will be separated into their solid and liquid compounds while the majority of the nutrients will be bound to the solid product. The liquid product can then be disposed without any restrictions, while the nutrient-enriched solid product can be pelletised and sold as a valuable storable organic fertiliser. A series of tests on the lab-scale has demonstrated the great potentials of the new technology although not confirmed on an industrial-scale prototype. Several technological development needs were identified and assessed feasible and a commercialisation concept was developed and assessed feasible as well. The legal framework was investigated, required employees and investments were calculated and risks were assessed.

VegWaMus CirCrop aims to develop commercial mushroom and vegetable production in an integrated food to waste to food system. Foodwaste treated in anaerobic digestion can be a multicomponent organic fertiliser and byproduct for plant and mushroom cultivation substrate. A large R&D greenhouse unit located next to a new large anaerobic digestion plant will investigate and demonstrate full utilization of output CO_2, heat and organic residue (digestate) from the AD. The project objective is closing loop between biogas production from food wastes and reuse of output. The project will indicate mushroom species which will be grown commercially on substrate based on digestate and vegetable plant grown rousing spent mushroom substrate. 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 aimed to develop a sustainable combined sanitation and 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 within a combined treatment system. 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. VicInAqua developed innovative multipurpose self-cleaning water filtration solutions adapted for sanitation of different wastewater streams, reused in Recirculation Aquaculture Systems (RAS) and agriculture irrigation. The VicInAqua solution permits a real-time monitoring and timely response thanks to an integrated efficient and intuitive sensor system. Power supply based on renewable energies adds to the overall solution's sustainability, combining high performance photovoltaic panels (PV) and a biogas facility (optimal utilisation of surplus sludge) with thermogenerators (TEG).

WASTE2WATTS (W2W) will design and engineer an integrated biogas-Solid Oxide Fuel Cell combined heat and power system with minimal gas pre-processing, focusing on low-cost biogas pollutant removal and optimal thermal system integration. Two cleaning approaches and hardware will be developed. One type will address small scale units (5-50 kWe), where a huge unutilised biogas potential resides (farm waste, bio-wastes from municipalities) - here sulphur compounds (H_2S and organic S) are removed by an appropriate solid sorbent matrix. Another type addresses medium-to-large scale units (≥500 kWe), which is the existing scale of landfill biogas and large bio-waste collection schemes - here sulphur compounds and siloxanes are removed among others by a novel cooling approach. A detailed full system model will be implemented, considering the biogas feedstock, composition fluctuations (and dilution) and pollutant signatures, and optimizing thermal integration with biogas-inherent CO_2 (for dry-dominant reforming) and digester heating, with the targets to maximise net electrical efficiency and minimise cost.

The project **ZeoBio-NG** aimed to provide small-medium biogas producers with a cost and operation efficient solution to upgrade their biogas to biomethane, that includes a biogas upgrading module developed from the seamless integration of existing and state-of-the-art biogas upgrading technologies. The module could upgrade biogas in small-medium biogas flowrates of 50-200 Nm^3/h, to produce high quality biomethane. The module has high efficiency, low energy requirement and significant lower costs that most of the available commercial products. The project carried out a comprehensive feasibility study to assess its innovative biogas upgrading technology, as well as to explore the market potential for the commercialization of the technology.

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 35 projects have been identified as addressing the research on biomass combustion, under H2020 RTD EU programmes.

AgroBioHeat project aims to produce a mass deployment of improved and market ready agrobiomass heating solutions in Europe. Engagement and matchmaking actions will lead to trigger many initiatives on agrobiomass for heat. To generate trust to market actors, the project will detect many cases running on agrobiomass and several cases will be approached, documented, visualized and visited by potential early adopters. The project will perform tests covering different market heating technologies and agrobiomass in order to generate reliable data on its emissions and operational performance, and to show the market and community the existing improved technologies. These results will contribute to the anticipated review of the Ecodesign regulation for agrobiomass boilers, while providing suggestions for suitable emission limits in the 500 kW-1 MW range facilities. Strategic plans for the deployment of agrobiomass for heating market will be drafted and discussed.

In the **ARBAHEAT** project, an existing 731 MWe Ultra-SuperCritical coal-fired power plant is transformed into a biomass-fired Combined Heat and Power plant by repowering with thermally-treated biomass produced on-site. This demonstration encompasses the transformation into CHP that will provide renewable local heat, enhancing the overall efficiency of the plant from 46% electricity-only to 70-90% in CHP mode. An integrated thermal pre-treatment process will enable utilisation of diverse sustainable biomass feedstock, minimising investment and operating cost. The thermal biomass upgrading process of ARBAFLAME will deliver biomass fuel with handling and milling characteristics approaching that of coal, allowing for retrofitting with minimal adaptations to the existing power plant. The biomass pre-treatment and heat delivery system will be physically integrated within the existing power plant. Eliminating several cost and energy intensive steps (steam production, pelletizing) will be investigated, towards more cost-effective final design.

The primary objective of **BELENUS** is to lower bioenergy CAPEX and OPEX by an average of 5 and 60% respectively. This will be addressed by preventing or mitigating corrosion as the main limiting factor through a holistic approach to prevent corrosion in the boiler, in particular in superheater (SH) tubes: new surface engineering: biomass corrosion highly resistant coatings; new strategies of welding and bending for coated tubes; and new online corrosion monitoring system. The BELENUS solution will impact on other LCOE parameters by improving efficiency in the conversion (up to 42%), increasing a 5% the operational hours of the plant and plant life time (5 years) and reducing the fuel expenditure of the plant by optimising its use and providing flexibility by allowing the use of different types of biomass. Modelling and lifetime prediction tools will be developed and cost analysis and Life Cycle Analysis (LCA) undertaken so the optimum materials and coatings are chosen from the durability, economic and environmental perspectives.

The **BioBur** project assessed technical, commercial and financial feasibility that confirmed the need of powerful bioheat solutions that reduce high-dependence from fossil fuels. The industrial biomass burner can convert conventional coal, diesel, or natural gas boiler into a biomass one at thermal power of 3-10 MW. It can use any kind of biomass available, contributing to circular economies by enabling industries to use their own by-products as feedstock for their production plants. The proposed multifuel biomass rotating burner (BioBuR) is efficiecnt (up to 98%), compact (50 % reduction in size) and economic (up to 75% price reduction) when comparing with grate-fired solution; by scaling it up to 3-10 MW and able to substitute to the fossil fuel burners within the food and beverages processing industry.

BIOBURNER proposes an innovative hybrid dual burner that will make biomass burners a technology adequate for industrial processes, with needs for continuous process heat. The project assessed the technical, commercial and financial feasibility of our project, the technical developments, an in-depth analysis of the target markets and prepared the execution plan for the development of the BIOBURNER prototypes. The bioburner is compact, safe, plug and play, scalable, cost-effective, efficient, reducing thermal energy cost by 50%, reliable, being able to operate automatically with two fuels and sustainable, reducing CO_2 emissions by 95%.

The main objectives of the **Biofficiency** project were increasing the efficiency of CHP plants by elevated steam parameters through solving and understanding of ash-related problems, reducing emissions (CO_2, particulate matter, CO, NOx, and SO_2), widening the feedstock flexibility using pre-treatment methods (torrefaction, hydrothermal carbonization and steam explosion) and optimizing ash utilization and nutrient recirculation. The **Biofficiency** project investigated how to handle ash-related problems in order to increase steam temperatures up to 600°C in biomass-based CHP plants, including pulverised fuel and fluidised bed systems. The project approach addressed current bottlenecks in solid biomass combustion, to to deepen the understanding of deposit formation, corrosion and ash utilisation by a variety of new, promising technologies.

The main objective of the **Bio-HyPP** project ws to develop and to demonstrate a full-scale Hybrid Power Plant concept as a reliable, cost-effective and fuel-flexible micro-combined heat and power system a full-scale technology demonstrator for gaseous sustainable biomass feedstock. The aim of the demonstrator is to prove the functional capability as well as to achieve high system efficiency with respect to fuel flexibility and optimized subsystems and subcomponents. Bio-HyPP concept is a combination of solid oxide fuel cells and a micro gas turbine, a technology solution for a biogas-fired combined heat and power (CHP) system addressing effectively requirements for highly-efficient, highly load- and fuel-flexible CHP systems with low emissions.

C-HEAT developed a cutting edge biomass boiler capable of working under condensing conditions that has been internationally awarded, surpassing from far the current state of art, in terms of performance (10% higher than high-end average boilers), ripping design (extremely compact with the best materials) and price (at least 20% less than comparable solutions). Thanks to a novel spiral heat exchanger that enhances 50% the exchange surface, C-Heat compact solution shows > 100% energy efficiency by capturing almost all latent heat of condensation of water vapor in the exhaust stream. In addition, an accurate control of the system enables low temperature applications (i.e. radiant floors). Until now, C-Heat has passed rigorous technical assessments, procuring international quality standards certifications and several units are well operating in real conditions.

The aim of this **CHP** project is the upscaling and commercialization of a developed CHP (combined heat and power generating system) comprising a highly efficient wood pellets fired steam engine (TRL7). The CHP power output is 50 kW electrical and 175 kW thermal power with 20% electrical and 90% overall efficiency based on wood pellets. The aim of of study was to investigate the market positioning and commercialization strategy of the proposed upscaled CHP in terms of size, pricing and market launch strategy. As this technology has base load capability, this would be a perfect supplement for the existing renewable energy systems like photovoltaics and wind.

In this **cleanFIRE** project the new pellet and logwood stoves combustion technology shall be further optimised in order to pass type testing at project end. While pellet stoves typically achieve low pollutant emissions during pre-commercial testing, these emissions often surpass certification limits when users operate them at home. Current solutions involve installation of extra filters that can double the investment costs of the entire heating system. CleanFIRE constitutes a milestone in pellet-based space heating because it enables for the first time an almost zero CO, OGC and PM emission free combustion without the application of extra dust filters.

The **CYCLOMB** project aimed 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). Cyclone tests carried out improved the effectiveness of the reduction of particle emissions, with an innovative geometry design. The improved the KSM biomass boiler allows to increase combustion efficiency up to 92% besides the development of an intelligent control system that integrates the control of the boiler and the cyclonic solution into one.

The objective for the **DEBS** phase 1 project has been to test commercial hypotheses in the market and to develop and advance the Dall Energy furnace further to implement the improvements from the prototype testing and demonstration already undertaken. Dall Energy has developed a new, disruptive biomass furnace, which integrates several independent innovations into a novel concept for conversion of biomass into energy with at least 10% lower investment and 40-60% lower operational expenses, while at the same time reducing emissions to very low levels. Cooperation strategy and project possibilities has been discussed and initial agreement about project development has been initiated.

Dall Energy has developed a new, disruptive biomass furnace that reduces dust and particle emissions by more than 90%: 30% lower investment; 50% lower maintenance costs; very wide load window; up to 40% reduction of fuel cost through increased fuel flexibility (wet biomass, organic waste streams, willow, etc.). The expected outcomes of the **DEBS project** are an adapted furnace design and a demonstrated and validated furnace. Dalkia has decided to build a first Gasifier unit from Dall Energy. The new heating plant in Rouen is based on the Dall Energy gasification technology and will supply up to 17 MW of heat to the network and run for more than 7 000 operation hours per year.

The objective of this **DeReco** study was to analyze and evaluate the markets including their technical and commercial requirements and competing technologies, leading to an elaborated business plan showing best entry market in Europe. DeReco proposes a device for small scale (1 to 50 kW) Waste Heat Recovery systems based on the Clausius Rankine Cycle (CRC) or alternatively on the Organic Rankine Cycle (ORC) technology and can substantially improve the efficiency of industrial processes, engines and facilities. Further applications are seen in the power generation through biomass combustion as well as in the geothermal and solar thermal energy generation.

This **DT4BIOMASS** project aims to develop a comprehensive and accurate biomass boiler model which can be adapted easily to simulate any biomass boiler and, in this way, to overcome the barriers to incorporate this technology to biomass boilers manufacturing/operator companies. Nabladot S.L. has available models to simulate any part of a biomass boiler excepting the fixed bed (or grate), which require the application of complex simulation techniques such as the Extended Discrete Element Method. The EU-funded DT4BIOMASS project is developing a biomass boiler computer model that is more suited to simulating any biomass boiler so that biomass operators can easily incorporate the technology.

EcoVapor project offers a smart steam boiler that will make steam production a very cost-effective (ca. 30-50% cheaper than typical boilers of low NOx emissions), energy-efficient (up to 95% overall), smart (modulation range 5-100%), and environmentally friendly alternative (only 80mgNOx/kWh emissions). ECOVAPOR solution comprises a pre-mix burner based on the inward flame novel design giving the boiler a large modulation range (5-100% output power), with an intake self-regulated system capable of mixing air/gas in the optimal ratio before blowing inside the burner. The project defined the functional requirements and needs of the target process plants, developed the basic software functionalities and scaled-up of the steam boiler design that were tested to confirm the design of the components of the boiler of the complete range and scale up of the prototype from 350 to 1000 kg/h.

The project **FLORIAN** proposes an intelligent device installed on the flue gas pipe used in wood log stoves which automatically regulates the draft inside it, optimizes the combustion process -21% increased energy efficiency and analogue gas and particle emission reduction. FLORIAN proposes solutions for efficient combustion conditions (i.e. reduced fuel consumption (i.e. cost efficiency) and particle emissions); safe installations and minimum user intervention (i.e. reduced refueling time). This offers an innovative device differentiated from traditional solutions due to its intelligent (embedded algorithm) and fully automated nature which combines both mechanical (flap, fan) and electronic parts (regulation, sensors, automatic controller).

The project **Heat2Energy** presents a new energy conversion technology for low-grade waste heat recovery, transforming thermal energy (80°C - 400°C) from different sources on demand in different kind of energy forms (mechanical, electrical energy or higher/lower temperature levels). The efficiency rate is much higher than for comparable ORC plants. The project objectives were to prepare the technical and economic data base for demonstrating the technology for waste heat recovery in a 300 kW pilot application to provide mechanical drive for the screw-type compressor to generate compressed air; to elaborate the business plan and finally to promote the technology in the various energy-intensive sectors. Depending on the source, the potential markets are: industry (waste heat recovery), residential (buildings), renewables (solar thermal, biomass, geothermal) and mobility (energy-efficient drives for ships, locomotives and trucks).

The **HPC4E** project aimed 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 are able to run combustion simulations required to design efficient furnaces, engines, clean burning vehicles and power plants. By developing complete model for the combustion of biogas, HPC4E established the conditions necessary to guarantee safe combustion. The project tabulated the chemistry of biogas composed of different elements and applied their findings to the simulation of industrial combustors. The use of super computers is highly efficient when running software to simulate different combustion phenomena.

HyBurn elaborated the technology roadmap for the selection of manufacturing technologies to ramp up and the market entry and market multiplication strategy for a in-situ premix combustion system. The burner developed enables the well controlled, more efficient and cleaner combustion of renewable gaseous fuels, hydrogen or (lean) biogas mixtures, landfill gas or (pyrolysis) process gases. The objective of the action was to find out how to enter the market for “Hydrogen-to-heat” solutions based on a unique technology and product portfolio enabling to address various needs.

The objective of this **HYBURN** study is to facilitate the transition to a reliable and cost-effective energy system based on carbon-free renewable power generation. HYBURN develops 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 is 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 strategic objective of the **IE-E** project was to develop a new heat-to-power engine in low-temperature ranges so that to recover and convert heat to power in a cost effective manner. The IE-E product is based on ORC technology equipped with a beyond the state of the art expander experiencing higher efficiency compared to ORC market available products. A first prototype has been designed, manufactured and tested, revealing the potential of this technology. Further work is required to validate and improve this concept and up-scale the expander to the commercial size of 20 kW rated power, so that to meet the decentralized biogas ICE market.

In the **INSERTRONIC** project, an innovative closed fireplace insert log wood combustion technology has been developed, ensuring very low gaseous emissions, highest thermal efficiency and high comfort. Beside the optimised combustion, the automated process control system including an automated remotely controlled ignition system are the most important improvements. The lightweight flexible insertion frame and modular panelling system guarantee an easily and quickly integration of the fireplace insert. Comprehensive test runs on the prototypes and test stands have been performed and evaluated. Final long-term test runs and CFD simulations have been done and optimization measures have been worked out and implemented in the final product design. Construction drawings of the final design of the flexible insertion frame and modular panelling system have been prepared and 10 field test units have been produced.

The project **Laelia Due** addressed a smart pellet stove that combines efficient heat generation with IoT. It integrates smart home appliances, collects its performance & surrounding air quality data & provides revenue-generating value-added smart services. The smart stove allows placement of installation orders from the local service providers, remote monitoring, diagnostics & preventive maintenance of the stove; user notifications on the quality of pellets & automatic adjustment of burning temperature; measurements of the indoor air quality, automatic notifications & emergency shutdown and notifications on pellet consumption rates & automatic pre-orders of the resupplies. The project validated the business potential together with the commercial and economic feasibility of Laelia Due stoves, and in particular the competitive advantage of the web and mobile direct sales channel, the additional value-added smart services and related business partners to implement them and the value proposition.

The **NanoORC** project aimed 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 project **MILESTONE** aimed to establish a new multi-scale framework to analyze and model turbulent combustion phenomena based on a new way to describe turbulence using so-called dissipation elements, to create new datasets using direct numerical simulations (DNS) and provide new analysis methods to develop and validate combustion models. MILESTONE performed very large Direct Numerical Simulation of complex flow including turbulence, combustion, and multi-phase phenomena such as sprays and atomization. The simulations run on massively parallel computers with more that 100.000 processors, employing hundreds of billions numerical degrees of freedom, and generating hundreds of terabytes of data.

The goal of the **ORC-PLUS** project is to validate, in a relevant industrial context, an innovative Thermal Energy Storage-TES system optimized for a mid-size CSP plant coupled with an ORC turbine of 1MWe. The validation in a relevant environment of this new model of CSP plant will permit to accelerate the development of local green smart grids. The project proposes to develop an optimized combination of innovative Thermal Energy Storage-TES (specialized for CSP scale 1-5 MWe) and engineering solutions to improve the number of production hours of an existing small CSP plant, located in a desert area and coupled with an ORC system. The project supports the electrification programmes of rural and semi-urban areas, creating new opportunities of investment in peripheral areas with positive socio-economic benefit. Final goal was to experimental demonstration of two different industrial prototypes of TES systems in relevant environment (TRL 6) and to validate the technology in a real operational environment and to demonstrate its feasibility (TLR7).

The project **POWERICE** addressed the small-scale (< 1 MWe) co-generation plants operating efficiently in a one-farm basis using rice straw, while tackling the issues of resulting combustion ash that causes slagging and fouling of furnaces. All steps of the overall process were analysed in order to increase efficiency, a simplified and robust fuel storage, reliable handling and feeding systems, simplified boiler operating conditions (pressure, temperatures, medium quality requirements), and reduction of specialized alloy metals in the boiler design to lower general costs of the heat source when using small ORC turbines. The optimal solution is a 300 kWe type ORC unit (100 kWe for Italy) recovering up to 710 kWth of thermal power from a boiler.

The **PyroTRACH** project aims to provide the necessary breakthroughs in our understanding of particles from biomass burning and their impacts. The project focusses on measuring highly uncertain but critically-important climate- and health- relevant properties of aerosols both from wildfire events that occur during summertime and from biomass burning for heating purposes during wintertime in highly populated urban environments. Novel state-of-the-art instrumentation, portable environmental chambers and well established measurement techniques will be applied in continuous measurements as well as intensive field campaigns to study the properties and evolution of the particulates from biomass burning as they age in the atmosphere. This allows a better understanding of the evolution and impacts of biomass burning aerosol and its impact on the Earth System and public health.

The **RECaPhos** project focuses on development of a novel method for phosphorus recovery based on the thermo-chemical reaction of sewage sludge, in the presence of CaO in a fluidized-bed reactor, assuring in the same time the destroy of dangerous pathogens, antibiotics and contaminations from fluidized bed combustion. The goal is to develop, optimize, and evaluate the novel method and to provide rules and data for process up scaling purposes. This will be achieved by means of development of innovative models to investigate the thermodynamic and chemical process taking place. Experimental data from host institution facilities and data from literature will be used for models validation and optimization.

The objective of the **SINTRAN** project was to prepare a feasibility study for the optimization, certification and commercialization of BIOFIVE technology and device that transforms humid organic waste (such as sewage sludge) into green energy (electricity) by combustion while extracting valuable materials from the remainder ash, like phosphate. The combustion tests proved that mono-incineration of sewage sludge the equipment is able to decontaminate and dispose of harmful and dangerous organic waste (and its mixture). The device can be used to reduce large amount of hazardous organic waste and it can be integrated into every waste disposal technology with economic and social impacts.

The **TASIO** project aimed to develop solutions to recover the waste heat using waste heat recovery systems based on ORC. A Waste Heat Recovery System was 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 project developed a concept of he direct heat exchanger linked to the ORC for the reuse of the heat of flue gases for the production of electricity. The project proved the possibility of using the conventional ORC process to recover and transform the energy of the flue gases of EII into mechanical energy for internal use (air compressors).

The **Exergyn Drive** addresses the use of low-grade waste heat of <120 ºC, usually 80-95 ºC from power production and its conversion into power. It converts LGWH to mechanical or electrical 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 TRL 9 and to be ready to produce and comercialise up to 35 x 10 kW Exergyn Drives™ per month. The closest competitor-technology is the ORC. The first prototype was successfully deployed to a trial site with output and efficiency exceeding targets when adjusted for trial site temperatures. The next generation engine was designed and tested.

The **TUCLA** 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. A very important aspect is to use the developed and available diagnostic techniques to assure experimental data in extremely challenging environments and together with modelling experts enhance the understanding of combustion phenomena. The project will use the diagnostic techniques to provide experimental data and enhance the understanding of combustion phenomena. The work done towards high-speed imaging demonstrated how structured illumination can be used to acquire a multitude of images using only a single detector that opens up for new diagnostic opportunities. Diagnostic techniques have been employed for studies of biomass combustion and gasification.

The overall objective of **VADEMECOM** was to drive the development of modern and efficient combustion technologies, by means of experimental, theoretical, and numerical simulation approaches. Significant progress has been made in experimental investigation of novel combustion technologies, the assessment and optimisation of comprehensive chemical mechanisms for MILD combustion, the development of novel turbulent combustion models and the definition of strategies for the Validation and Uncertainty Quantification. Significant progress was made toward developing optimised and validated comprehensive chemical mechanisms for MILD combustion conditions, and for developing models that can include realistic chemistry in the simulation of combustion systems.

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.

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, under H2020 RTD EU programme.

The **SteamBio** project developed a mobile processing concept for the efficient pre-treatment of agroforestry residues through superheated steam processing. The efficiency of the process is based on working in a controlled atmosphere of steam, which is generated from the moisture in the materials and thus inert due to absence of oxygen. The concept has been proven at pilot scales to torrefy assorted biomass materials into hydrophobic and grindable solids with value-added volatile compounds as a sidestream. The continuous superheated steam processing technology platform is scalable and has been proven technically at industrial scales with temperatures up to 300 °C. The project also deployed a demonstration unit with a throughput of 150 kg/hr in different locations. Recovered condensate from the superheated steam process has already been shown to contain commercially relevant quantities of biochemicals in addition to the torrefied biocarbon mass.

The **TOPIS-BioCirc** project will study the feasibility of torrefaction of pulp and paper industries sludge and integrating it with microbial conversion to produce bio-coal, bio-methane and volatile fatty acids. Torrefaction of dewatered PPIS will be carried out in order to establish the biofuel characteristics of torrefied sludge. Later, anaerobic digestion of torrefaction condensate produced through the torrefaction of PPIS will be studied at varied operating conditions in order to establish the production potential of bio-methane and volatile fatty acids. Finally, the proposed process integration will be simulated to a commercial scale from laboratory experimental results in order to evaluate the techno-economic and environmental feasibility. Pprocess simulation will be carried out to investigate the overall feasibility of the process at industrial scale.

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 conceptual design of the Torero plant has been completed and the future location determined. After evaluating a number of alternatives the initial idea of integration with the sinter plant was retained. The currently bio-coal production with the demonstration reactor will be within a range of 30000 - 50,000 t/year. The ambition of the project remains a yearly production of 50 000 tons/year, but that is estimated to be the maximum achievable after optimising the production process conditions.

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 m.

4.4.3 Pyrolysis: EU and SET Plan projects

A number of 9 projects have been identified as addressing the research on biomass pyrolysis under H2020 RTD EU programme.

A new biorefinery approach developed in **Bio4Products** applies a short thermal treatment at elevated temperature (fast pyrolysis) followed by a low temperature fractionation that keeps the key chemical functionalities intact in separate, liquid, depolymerized fractions. Fast pyrolysis is a thermal treatment that converts solid biomass into a liquid called fast pyrolysis bio-oil (FPBO). This FPBO consists of components derived from the de-polymerization of cellulose, hemicellulose and lignin. FPBO can be used directly for energy purposes, upgraded to transportation fuels or separated into functional groups, i.e. pyrolytic lignin and pyrolytic sugars. A main deliverable of the project is the construction of a fractionation demo-plant. The design capacity is 3 ton of pyrolysis liquid per day producing pyrolytic sugar and lignin.

The objective of **ECOCAT** project was to investigate and improve the economics of the catalytic pyrolysis of biomass by reduction of catalyst-related operating costs and optimization of catalyst selectivity. This is going to be achieved through utilization of microporous zeolites modified with mesoporosity. Experimental procedure were planned for the systematic study of mesoporosity through assessment of catalyst performance, such as activity, selectivity, coke suppression and deoxygenation. Increased activity and selectivity is expected to result from increased accessibility of larger molecules to the zeolite acid sites. The lifetime can be extended through the usae of materials more reactive to biomass metals, obtained through a better understanding of the mechanism of poisoning from biomass metals and modification of the catalyst.

The **FLEXI-PYROCAT** project aimed to develop optimised catalysts that deliver high quality yields of the targeted high value products. Process integration of the pyrolysis technology with catalysis aims to deliver an innovative technology with full flexibility to alter process conditions and/or catalytic reactions to deliver the targeted high value products. 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. Scale-up of the pyrolysis-catalysis process was undertaken in order to understand the implications in process development and further to continuous processing. Process modeling of the scale-up plastic waste pyrolysis catalysis system was undertaken. A techno-economic assessment was produced based on a mass and energy balance of the process and estimated cost data.

The **Hydrogreen** project carried out a feasibility study defining a feasible roadmap in all technical, commercial and financial aspects to achieve Hydrogreen industrialization. Hydrogreen is a pyrogasification-based process where biomass (wood, wood waste, straw) is converted, with optimum efficiency, into energetic hydrogen and decarbonated CO_2. The main activities are: upgrading the preparation of our raw material, optimisation and validation of hydrogen production, setting up our hydrogen purification, storage and distribution systems, and the integration of all the technologies into the demonstrator unit.

The **PYROCRACK** project performed a feasibility study to achieve the completion and optimization of the current scale lab plant and a real dimension pilot plant with performance and very low emissions certifications. PYROCRACK uses a patented pyrolysis process to treat MSW obtaining a mixture of liquids, gases and solids with high energy content and a novel Thermal Cracking process that improves the quality of this mixture. Pyrolysis decomposes waste without using O_2 which avoids pollutant emissions transforming waste into high value products. The market analysis demonstrates its commercial viability and justify the investment in the innovation. Competitors have been studied and the market barriers introduction have been identified and mechanisms have been set to overcome them.

PYROCHEM has proposed to investigate the fundamentals of biomass fast pyrolysis to improve the understanding of fast pyrolysis mechanisms and the process and design of reactors. The project aimed to provide insight in pyrolysis chemistry to reveal key mechanistic details of the formation of bio-oil and to detail the impact of the interactions between lignocellulosic biopolymers on bio-oil's quality. The project followed experimental approach that included: (i) deconstruction of raw and 13C-enriched biomass; (ii) fast pyrolysis of raw and extracted materials under steady-state conditions for studying kinetic-controlled chemical reactions; (iii) analysis of pyrolysis products using in-depth spectrometric techniques; and (iv) theoretical evaluation of primary fast pyrolysis reactions.

PyroTech proposed a solution that will help transition coffee farmers at their production capacity to a more sustainable, resilient, and profitable practices. PyroTech produces biochar, out of agro-food waste and is a powerful soil enhancer while the excess heat released can then be used for drying purposes. The project PyroTech determined the technical options to boost the performance and return on investment, that include ideal pre-drying unit configuration, the automation layout, material changes to reduce Capex and Opex. It determined the optimization criteria for PyroTech, particularly the process parameters which has led to the final process specifications. The project also determined the best business models as well as key partners for wider PyroTech market adoption and analysed the financial viability of PyroTech during commercialisation.

The overall objective of **Residue2Heat** was to enable the utilization of ash-rich biomass and residues in residential heating applications through the production of fast pyrolysis bio-oil and its distribution to residential end-users. The produced fast pyrolysis bio-oil should fulfil applicable specifications for replacement of domestic heating oil and comply with regulations. The ash is recovered from the fast pyrolysis process as a separate stream, and recycling and/or re-use will be assessed. Existing highly efficient condensing boilers are used as starting point in the project, as well as a proven, low emission type of burner that are then modified to enable fast pyrolysis bio-oil as fuel. Various biomass feedstocks have been used to produce fast pyrolysis bio-oil at different production facilities and several methods have been developed to condition the bio-oil.

The **SmartCHP** project designs a novel cost-effective and flexible small-scale cogeneration engine using biomass to produce heat and electricity. The main novelty is the use of fast pyrolysis bio-oil from different biomass types in an efficient diesel-engine based CHP. It will develop a smart and flexible, small-scale CHP unit (100-1,000 kWe) fueled with fast pyrolysis bio-oil originating from different types of biomasses and/or residues. Fast pyrolysis converts biomass into a uniform liquid intermediate called FPBO, and the process is characterized by a high feedstock flexibility. Integrated with variable renewables such as wind and solar, the new system will generate power from biomass when the electricity provided by wind and sun is unavailable, thereby, securing the supply of renewables. The final result of SmartCHP is an integrated system consisting of an engine, boiler and flue gas treatment system adapted and optimized to run on FPBO (TRL 5).

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 m.

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 m.

4.4.4 Hydrothermal processing: EU and SET plan projects

A number of 7 projects have been identified as addressing the research on biomass Hydrothermal processing under H2020 RTD EU programme.

The objective of **HTC4WASTE** project was 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. The small scale tests prove that HTC is able to fully convert all forms of bio- waste, sewage sludge, and also any form of mixed heterogeneous bio-wastes streams into a high value carbon neutral fuel or agriculturally beneficial biochar. HTC business case demonstrated that recovering organics into a biofuel for onsite use has significant benefit to operational profitability. The project developed techno-economic analyses of implementing the HTC system into daily operation.

The main purpose of project **HTCycle** was to carry out a feasibility study report about the sewage sludge production and disposal methods in order to find potential markets for the promotion of the Hydrothermal carbonization technology (HTC) as a high potential sewage sludge treatment method for the upcoming years. The project HTCycle has the objective to demonstrate and commercialize a proprietary technology for hydrothermal carbonization (HTC) of sewage sludge, showing clearly technical and economic ad-vantages against the current sludge incineration method. The aim is to increase the amount of sludge converted into high value products such as fuel, activated carbons for water treatment, recovered phosphorus, soil remediation material, carbon sequestration schemes and other applications. The HTCycle process turns the present sewage sludge disposal (incineration) from a costly process into an income-generating activity.

The project **HTSew** has the objective to demonstrate and commercialize a proprietary technology for hydrothermal carbonization (HTC) to the conditions of sewage sludge (HTSew), showing clearly technical and economic advantages against the current sludge treatment methods. It aims to reduce the treatment costs for the sludge, providing an innovative technology, which is at the same time beneficial for the environment. The HTSew process turns the sewage sludge disposal from a costly and environmental unfriendly process into an income-generating activity, by reducing the treatment costs and enhancing locally the industrial sector. The project has carried out tests at industrial scale (5 tons) with their in-house prototype which have shown that sewage sludge is a technically viable feedstock for HTC. The feasibility study assessesed in depth the existing sludge disposal markets identifying and characterizing the regions where the current market for sludge disposal is ready for the uptake of HTC.

The **Hydrofaction** project aimed to develop the Steeper Energy Aps (SEA) innovative hydrothermal liquefaction technology platform (from TRL 6 to TRL 8). 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 project completed a conceptual engineering study, refined the strategy to bring Hydrofaction Oil to the market, undertaken R&D on the hydrotreating of Hydrofaction and developed/secured additional intellectual property in the form of patents. A conceptual engineering study and a basic engineering study have been undertaken. The state of the art of Hydrofaction has progressed through the execution of multiple engineering studies on the ISDDP and commercial facilities.

The objectives of **HyFlexFuel** project includes advancing and demonstrating HTL conversion from diverse biomass feedstocks and increasing heat integration and product recovery (TRL 2-4 to TRL 5). The project also aimes 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 currently less mature process step of catalytic hydrotreatment of bio-crude is being investigated through a parametric study of process conditions, targeted catalyst development to be demonstrated on a continuous system.

The objective of the **NextGenRoadFuels** project is to apply advanced HTL technology and subsequent upgrading to a selected range of low value/cost, concentrated biogenic residues from urban activity, in order to obtain cost competitive, sustainable drop-in quality synthetic gasoline and diesel fuels. New innovative process steps will be designed and existing steps optimized to address the additional challenges encompassed by such feedstocks, exemplified by sewage sludge, food waste and construction wood waste (termed urban feedstocks), with the objective to reach similar performance as for lignocellulosics. The project aims to establish fundamental pretreatment process and parameters to provide highest possible organic dry matter content in feedstock slurry and efficiently remove valuable inorganics that can have added value as organic fertilizers and/or soil improvers. It also aims to establish HTL processing parameters giving highest possible carbon and energy yields to oil phase - and to establish efficient upgrading schemes to bring the HTL intermediate bio-crude to drop-in gasoline and diesel fuels.

The **REBOOT** project will create a wet waste valorisation technology, recovering phosphorous from wastes while generating carbon neutral fuels and a carbon sink in the form of carbon materials. The project will employ hydrothermal liquefaction (HTL) which uses high temperature and pressure to produce a liquid product similar to petroleum termed bio-crude. The complex hydrothermal chemistry of salts can only be exploited on such advanced reactors that are currently beyond state-of-the-art. The specific objectives of REBOOT are: (1) mechanistic understanding of salt behaviour in multi-phase hydrothermal systems with the aim of full recovery. (2) Develop tailored strategies for in-situ jet fuel synthesis. (3) Establish microbial electrolysis cells for in-situ hydrogen production and nutrient recovery. REBOOT is being carried out on pilot continuous reactors, where the challenging physical conditions can be explored, exploited and new engineering solutions developed.

The **bioCRACK** pilot plant (SET-Plan flagship project) with a biomass capacity of 100 kg/h 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 (750 ktonnes/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 17 projects have been identified as addressing the research on biomass gasification under H2020 RTD EU programmes.

The **BIOMASS-CCU** project aims to develop and maintain long term collaborations between universities in the EU with China and Australia to advance biomass gasification technology. The proposed technology adrresses integrating CO_2 capture and utilisation with multifunctional catalyst materials and enhance the economic feasibility by producing high value alkenes from CO_2 using conventional and advanced non-thermal catalysis. Extensive training and knowledge transfer activities will be carried out to enhance career development of the project participants. This project will provide an innovative and economic biomass waste gasification concept and contriibute to the development of advanced CO_2 capture and conversion technologies. Techno-economic and life cycle analysis will be carried out to justify the advantages of the proposed biomass gasification technology.

The **BLAZE** project aims at developing Low cost, Advanced and Zero Emission first-of-a-kind small-to-medium Biomass CHP. This aim is reached by developing bubbling fluidised bed technology integrating high temperature cleaning & conditioning system (IBFBG, that can convert heterogeneous feedstocks in a syngas with zero particulate matter and ultra-low tar and contaminants content), an integrated high temperature gas cleaning approach for HCl and H2S removal and an innovative key component for thermal and chemical integration of solid oxide fuel cell. The technology is developed for a CHP capacity range from small (25-100 kWe) to medium (0.1-5 MWe) scale using a range of feedstocks (forest, agricultural, industrial and municipal waste also with high moisture, ash and contaminants content), high efficiencies (50% electrical versus the actual 20%), low investment (< 4 k€/kWe) and operation (≈ 0.05 €/kWh) costs as well as almost zero gaseous and PM emissions, projecting electricity production cost below 0.10 €/kWh.

The aim of the **CLARA** project is to further develop Chemical Looping Gasification (CLG), which has by now only been investigated in lab-scale up to 25 kWth feedstock input, using a broad range of pilot plants up to a size of 1 MWth. The innovative CLG process uses an oxygen carrier that is cycled between a fuel and an air reactor to provide oxygen for partial conversion of the biomass feedstock. One of the benefits of CLG is that high quality syngas with low nitrogen content can be produced without an air separation unit. Avoiding air separation has high potential to improve the overall conversion efficiency and the economic feasibility of biomass gasification. Concepts for pre-treatment of biogenic residues are developed to enable their use for CLG, and an innovative syngas cleaning concept is established for reduction of capital costs.

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 **CONVERGE** project will demonstrate 5 unit operations in 3 grouped processing steps (pre-processing, valorization & enhanced methanol), taking these new combinations from the discovery stage (TRL 3) to development stage (TRL 5). The innovative configuration will reduce the total number of unit operations needed to achieve the conversion of secondary biomass and waste streams into green biodiesel and intermediate green refinery products. Each unit can be implemented as a stand-alone function within a modified state-of-the-art technology chain and thus provide immediate performance and energy efficiency improvements. Moreover, the units when used together have synergies that allow even more efficiency gains.

The project **EFFIGAS** analyzed the implementation of the technology from TRL 7 to TRL 9 and carried out research and analyses concerning various fields: 1) technical analysis and plan; 2) commercial plan and FTO analysis; and 3) financial analysis and plan. The developed technology proposed an innovative wood gasification plant which enables very low tar production and thus an easy and high efficient process of syngas (23-24%). A pilot system, EFIGAS, has been designed and developed, able to produce, in a stable way, and transforming different kind of waste, including agricultural and industrial residues, a good quality highly calorific syngas with very low content of tar (<0.3 g/Nm^3), achieving a higher efficiency (28-30%) with a very competitive price.

EUWaste project aims to conduct a feasibility study, which includes market analysis, production scale-up and business model and sales strategy development), first focusing on the medical waste utilization and further on other potential segments of waste management. EUWaste uses technology of gasification that allows utilizing waste of different type with a minimum environmental footprint and emission. Moreover, the use of gasification technology allows obtaining synthetic gas during the gasification process, which in turn can be used as a source of alternative energy for heat production. Waste categories include hazardous waste, such as healthcare waste, oil-contaminated waste, pesticides, solid and liquid waste and sludge containing hazardous substances, and other kinds of waste (agricultural waste, unsorted municipal solid waste, etc.).

The **FLEDGED** project will deliver a process for bio-based dimethyl ether production from biomass, combining a flexible a flexible sorption enhanced gasification (SEG) process and a novel sorption enhanced DME synthesis (SEDMES) process to produce DME from biomass with an efficient and low cost process. TRL5 validation tests have been carried out in the 200 kW pilot facility operational flexibility of the flexible sorption enhanced gasification (SEG) process was demonstrated, as well as novel sorption enhanced DME synthesis (SEDMES) tests with different catalyst/sorbent mixtures have been carried out. The techno-economic analysis of the complete FLEDGED process has been supported by the SEG models.

The project **FLEXCHX** project develops a flexible and integrated hybrid process combining electrolysis of water with gasification of biomass and catalytic liquefaction. The project is aimed at creating a method for managing the seasonal mismatch between solar energy supply and the demand of heat and power. The FLEXCHX concept proposes a method to produce combined heat and power should be produced in variable renewable energy-dominated power grids, and to use of excess solar and wind energy in combination with biomass residues. The FLEXCHX process can be integrated to various combined heat and power production systems, both industrial CHPs and communal district heating units. In the summer season, renewable fuels are produced from biomass and hydrogen; the hydrogen is produced from water via electrolysis that is driven by low-cost excess electricity from the grid. In the dark winter season, the plant is operated only with biomass in order to maximize the production of the much needed heat, electricity and FT hydrocarbons.

The **FlexiFuel-CHX** project aimed at the development of a new fuel-flexible and highly efficient residential biomass heating technology, developed for a capacity range of 20 to 130 kW (fuel power) as a solution for a wide range of residential-scale heating applications. It should be based on an existing small-scale fixed-bed updraft gasifier directly coupled with a gas burner and a hot water boiler. A Low-NOx gas burner was developed (also for N-rich fuels). A hot water fire tube boiler was developed which is able to cope with a broad range of biomass fuels. A novel fuel flexible flue gas condensation technology with an integrated condensate neutralisation stage and an automatic cleaning system was developed, which is tailored to the demands of condensing flue gases from the combustion of a wide fuel spectrum also with elevated S and Cl contents.

The **FlexiFuel-SOFC** project aimed at the development of an innovative, highly efficient and fuel-flexible micro-scale biomass CHP technology consisting of a small-scale fixed-bed updraft gasifier, a gas cleaning unit and a solid oxide fuel cell (SOFC). The technology developed is for a capacity range of 25 to 150 kW (fuel power) and thus be applicable for micro-scale CHP applications. The gasifier, the gas cleaning unit and the SOFC system as well as the whole CHP system have been further developed based on the evaluation of the test run results and the experiences made during plant operation. In total more than 250 hours of CHP operation have been reached and TRL 5 could be achieved. Based on these promising results, a final system design has been worked out, which shall form the first step for later industrialisation.

The **GAREP** study evaluated the technical and economic feasibility of applying the developed wood GasEK gasification technology for mid-range (250-1500 kWe) Combined Head and Power (CHP) plants, to define the best strategy for the technology commercialization, validate the technical data for product development and update the freedom-to-operate study. The technology entails a patented central nozzle system which makes it possible to develop larger gasifiers producing low tar level gas that would allow to use local biomass for producing heat and electricity. The technology allows the use of a wide fuel spectrum applicable (wood pellets, wood chips, SRC, selected agricultural fuels like agro-pellets, fruit stones/shells) allowing high gross electric (40%) and overall (90%) efficiencies as well as equal-zero gaseous and PM emissions.

HiEff-BioPower 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) and to achieve at the end of the project a TRL of 5. The technology allows the 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 for dust, HCl and S removal and tar cracking within one process step as well as a SOFC system which tolerates certain tar amounts. Technology development is based on process simulations, computer aided design of the single units and the overall system, test plant construction, performance and evaluation of test runs.

The **PlasmaPower** study has assessed the technical, commercial and financial feasibility of a technology platform for the high efficient conversion of waste biomass feedstock into energy via hydro-catalytic plasma gasification. PLASMAPOWER is an innovative (based on hydro-catalytic plasma arc technology), efficient (2 kWh per kg biomass vs. 1.1 kWh of conventional gasifiers), and cost-effective (electricity produced 2x times cheaper than other off grid technologies) biomass gasification system that produces sustainable power from the valorisation of low value biomass feedstock (i.e. forest debris and nut shells).

The objective of the **RENEGAS** project was to develop a feasibility study for an advanced downdraft gasification system that uses bio waste in the form of low grade waste wood or waste such as SRF or RDF to produce clean and high quality synthetic gas (syngas) that can generate heat and electricity (CHP). A business model for the successful commercialisation was developed. The downdraft gasification technology allows converting biomass and other feedstocks into valuable synthesis gas (syngas), capable of directly fuelling standard engines to generate heat and power (CHP). The patented processes includes 7 stages of syngas cleaning and cooling which ensures that its product gas is ultra clean and of the highest quality.

The main objective of the **TES** project was the realisation of a pilot plant and market introduction of a highly efficient and flexible biomass trigeneration system. The small biomass TRIGENERATION system is able to recover and valorize poultry manure (and other manure or biomass types) by gasification, then using the produced energy for heating, cooling and electricity generation, with the particularity of being adaptable also to small farms. This solution avoids disposal and soil contamination problems, substitutes the today used fossil fuels thus achieves important benefits for farmers not only in terms of economic savings but also in environmental terms of CO_2 reduction. The economic saving on the long run will increase their competitiveness.

The overall objective of the **Waste2GridS** (W2G) project is to identify the most promising industrial pathways of waste gasification and solid-oxide cell (SOC) integrated power-balancing plants (W2G plants in short). The project aims are to perform a preliminary investigation on the long-term techno-economic feasibility of W2G plants to meet different grid-balancing needs and to identify several promising business cases with necessary preconditions. The results of the project will further enhance the knowledge exchange and interaction among different key players (manufacturers, investors, and research institutions), provide useful guidelines for technology development/deployment and market positioning, increase long-term competitiveness and leadership of relevant industries, and provide knowledge for policy support on W2G plants.

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 MWe. 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 m budget, including €19 m 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 €88.5 m.

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 €203.7 m.

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.

4.5 Algae for bioenergy: EU and SET Plan projects

A number of 25 projects have been identified as addressing the research on algae production for energy production under H2020 RTD EU programmes.

ABACUS aimed at the development of a new algal biorefinery for high-end applications 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 of target products by online monitoring and automated control of photobioreactors with the development of specific sensors. A number of 31 micro-algae/cyanobacteria species were included into the screening process at lab scale. A suite of standard methods, for algal cultivation, biochemical analysis and genetical engineering was developed and applied. Pilot-scale cultivation of 7 algae strains was performed, focussing on scale-up of cultures, media optimization, water treatment and recycling, and PBR improvements in order to reduce maintenance and operational costs. Green extraction and fractionation/purification procedures employing innovative compressed fluids were developed.

ACCORDION is a platform for industrial scale production of high quality microalgae, at lower energy and decreased production cost, compared to other solutions. The technology describes the unique wave configuration comprising the frame work of the bioreactor, which contributes to higher productivity and lower cost of production and investment when compared to competing technologies. The modular design of this closed system greatly minimises the risk of contamination and can be easily adapted to large scale production. The Accordion bioreactor is applicable for photoautotrophic, mixotrophic and heterotrophic microalgae production. This project accomplished a full analysis of the technical and business potential of Accordion bioreactor, expanding its knowledge of the aquafeed market, including regulations, standards, market size and competitors.

Algae4A-B seeks to combine both basic and applied biotechnology research with state-of-the-art biomass production technologies to develop novel microalgae based products. The main objective is the characterization and the production of application customised microalgae biomass, as a source for high-added-value products. Despite their enormous potential and biodiversity, a surprisingly small number of microalgae have been analysed and only a handful of strains and derived biomolecules are currently used in health and cosmetic applications. The diversification of microalgae biomass production towards two independent applications will allow the microalgae industry to gain access to alternative markets. New facilities for microalgae culture under different conditions have been set up and trials were performed for the development and optimization of low input application-based culture systems.

BIOT objective in this proposal is to determine the techno-economic feasibility of transforming algatec+ in a closed-loop system by including two auxiliary services: (1) Open pond pre-treatment and (2) algae biomass valorisation as biofertiliser for the own olive fields. BIOT has coordinated two projects within the FP7 SME instrument programme to respond to the need of olive oil producers by offering an optimised biotechnological recycling solution for olive washing wastewater using photobioreactors (PBR). The technical viability of the process in industrial end use conditions has been sufficiently demonstrated in these two past projects: algatec+ treats olive washing water efficiently so that treated water complies with wastewater legislation, and treated water can be reused.

The project **AlgCoustics** addresses the production of aquatic biomass that can provide renewable energy (e.g. biodiesel, bioethanol and biogas) as well as high-value molecules such as carotenoids, fatty acids, carbohydrates, proteins and food fibres, which can be used in food, feed, cosmetics, biomaterials, nanostructures and pharmaceutical industries. Selective and economically feasible extraction and separation technologies will need to be developed and implemented. Significant microalgal cell disruption and extraction advances have been recently made by employing external fields such as lasers, ultrasonic waves and microwaves, in combination with less aggressive solvents and ionic liquids. The project proposes a single-step disentanglement and separation of microalgal high-value components by using acoustic waves at different frequencies allowing thus a complete process fine-tuning and eliminating the need for chemicals. Moreover, by including our previously-developed ultrasound disruption technology, the whole cell breakdown, extraction and separation steps could be reduced to one single process governed and finely-tuned through the employed frequency ranges.

The project **AORTA** carried out a feasibility study on its innovative AORTA technology for sustainable utilization of seaweeds. The feasibility study includes examining the technical- and economic viability, identification of specific technical risks, raw material risks and alternative sources in order to proof the viability of the technology and highlight the economic benefits. The proposal is outlining the need for elaboration of vital commercial elements in a Business Plan, including development of an Organizational and Financial strategy. The concept aims at total utilization of seaweed by a multiproduct blue biorefinery.

The **AORTA2** project proposed a complete and verified technology for harvesting and processing of seaweed. The harvesting technology opens for a new, innovative and environmentally friendly way of harvesting seaweeds, with no damage to the seabed or surrounding marine environment. State-of-the-art seaweed-industry only utilises about 15% of the harvested raw material and causes massive pollution. Demonstrating that seaweed harvesting can be done without dredging the seabed may lead to restrictions in the current business, but it may also create new opportunities. This will also harvest and process seaweeds without chemicals with long toxicity such as formalin, which will greatly improve environmental impact and product quality.

The **AQUACOMBINE** project proposes a new approach to valorise the woody residue of Salicornia (a salt-tolerant plant that grows in saline farmlands) for biochemicals and bioenergy production. The project will also investigate the use of aquaponics to optimally use all Salicornia fractions to create nutrient-rich fish feeds. The project AQUACOMBINE will also examine the combination of aquaculture and Salicornia farming creating synergies such as formulation and test of phyto-chemicals rich functional fish feed and formulation and test of protein and lipids rich fish feed. The outcomes of this study will enable Salicornia farmers and aquaponics farms to utilize all fractions of the produced biomass and produce value added HCAs, functional fish feed, and bioenergy. This will create new circular industries with co-production of food, pharma, and bioenergy from this new sustainable type of crop with very little or no production of waste streams.

The **BEAL** (BioEnergetics in microALgae) 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 project will determine the extent and diversity of anaerobic fermentation pathways in microalgae that make it possible to tolerate hypoxic or anoxic environments for a limited period of time.

The **BIOMIC-FUEL** project aimed the development of improved photonic materials that can be used to maximise algal growth in order to radically transform the algal biofuel sector. The project addresses a key challenge for making microalgal production commercially feasible that requires the improvement of the spatial efficiency at which algae can grow, because high cell densities lead to low photosynthetic efficiency as a result of self-shading. The development of photobioreactors that provide algae with artificial irradiation and regulate the flux of gases is a key approach to maximise algal photosynthesis. The specific objectives include: 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 objective of the **BIORECYGAS** innovation project is to scale-up the capacities of the BIORECYGAS technology and perform a market demonstrator relevant to the main target industries: steel industries, concrete companies, oil&gas refineries, chemical industries, heavy industries and agricultural facilities for the final deployment of BIORECYGAS to the global market. The BIORECYGAS technology, developed and pilot tested by ALGING, has demonstrated that removes 95% of CO2 and NOx from a simulated flue gas, beating the average 70-90% efficiency of the BAT technologies from NOx elimination and reducing 95% the need of CO_2 emission allowances. BIORECYGAS uses the extracted CO_2 and NOx as feedstock to grow Chlorella and other algae strains producing a biomass stream. The project performed a deep market search on international two-sided market of NOx and CO_2 emitters and algae based product consuming industries, acquiring a deep comprehension of the particular dynamics of each market, key stakeholders.

The overall objective of **BIOSEA** 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). **BIOSEA** aims at developing innovative methodologies in algae cultivation and process optimization, in order to increase the bioactive compounds production and cost reduction. For macroalgae cultivation are employed novel textile materials and optimized algae culture processes in optimized photobioreactors. Regarding microalgae cultivation, it is applied a new scalable PBR design based on mesh-ultra-thin-layer technology (MUTL) working principles. BIOSEA aims at using technologies that overcome the gaps existing in the conventional solvent extraction, by focusing on different pre-treatment and alternative extraction methods and on optimizing multi-step extraction processes, obtaining a cascading biorefinery approach including pretreatment, fractionation and conversion technologies.

The **Brevel** project developed a photobioreactor that can produce microalgae on an industrial scale at low costs. This system allows for microalgae production to become affordable and enables the stable cultivation of microalgae at a high capacity and resource efficient method. The core innovation lies in the internal volumetric illumination by concentrating and transporting sunlight by optical fibers that distributes sunlight to microalgae cultures effectively and efficiently. The photobioreactor is fully automated and relies on advanced image analysis, machine-learning and constant online monitoring and control technologies and has a capacity that is 400% higher than current microalgae cultivation systems and affordable cost. A market research has been conducted to map potential customers according to geography, size and openness to innovation.

This **CMHALGAE** project aimed to achieve a significant cost reduction by using multifunctional nanomaterials to combine multiple unit operations in downstream processing (harvesting, dewatering and cell disruption) into a single technology. The overall objective of this project was to develop a bio-based and reusable cellulose magnetic hybrid (CMH) nanomaterial that can be used for combining flocculation, cell disruption and dewatering of microalgae. This CMH nanomaterial would be able to achieve a critical cost reduction in microalgal downstream processing and advance large-scale microalgae production towards commercialization. This project integrated several promising recent breakthroughs in nanotechnology for downstream processing of microalgae into a single technology with cellulose magnetic hybrid nanomaterial to decrease the downstream processing costs in a microalgal biorefinery.

The project **ECO-LOGIC GREEN FARM** aimed the construction of an innovative production plant integrating highly performing algae cultivation in high-tech photobioreactors (PCBs) able to capture and reuse CO_2 with a syngas CHP using self-produced wood chips as a source of carbon, required for the photosynthetic process of microalgae, while its heat will be used for the thermal control of algal cultures and for heating/cooling of the company premises. The project developed a line for microalgae production, including PBRs for research on algae followed by the pilot line testing and the technological performance verified in real operative conditions. The most promising algae strains were selected for production. The project includes the construction 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.

The **INDALG** project addressed the issue of wastewater treatment by proposing a sustainable, chemical free solution for the treatment of process and wastewaters (WW) and the recovery of valuable materials through the use of microalgae as an industrial process to treat wastewater from agricultural, industrial and municipal sources. The project relied on a novel patented wastewater treatment process that uses microalgae to remove nutrients from wastewater effluents. The algae produced can then be separated out and valorised through various routes such as; fertiliser production; biogas; bioplastics; feed stock for green chemistry. It built a commercial demonstrator of its process for the treatment of municipal wastewaters, optimising its process for the treatment of industrial effluents and to develop methods of recovering value from the algal biomass. The project has worked with industry partners to identify the work required and end-user needs to prove its technology & develop its process to commercial readiness.

The objective of the **INTERCOME** project was to validate the microalgae production process which captures real flue gas emissions from a combined cycle plant in real environment developing AlgaEnergy's production facilities from TRL 7 to TRL 9. The project's objective was turning a demonstration production plant into a commercial industrial facility, which is called to be the European Flagship of microalgae production facilities. The project validated the process and further developed AlgaEnergy's production facilities guaranteeing a high quality supply of microalgae throughout the year. The project team designed and implemented a modulated production plant, and elaborated an operation protocol to simultaneously culture various microalgae strains without risking contamination. They modified the operational facilities to ensure the culturing capacity during seasons with suboptimal temperatures. The project also stabilised microalgae biomass to be produced in different delivery formats such as fresh paste and freeze-dried. It conditioned the processing facilities by making the necessary production layout adjustments and equipment upgrades.

The **IPHYC-H2020** project addressed a novel patented treatment process uses microalgae to remove nutrients from wastewater treatment effluents and meet increasingly stricter discharge consents for the concentration of nitrogen (N) and phosphorus (P) in wastewater effluents. The system uses a microalgae in an innovative modular internally lit bioreactor system to ensure a lower energy treatment process compared to other treatment technologies. This process is designed to require no chemical additions and produces minimal waste and generates a ready-to-use biomass as a waste product. The project performed a market study to determine the best approach for entering the market for P removal in wastewater effluent by marketing the solution under different local regulations; determining market size, growth trends and competition.

MacroFuels aimed to produce advanced biofuels from macro-algae (ethanol, butanol, and biogas). The project demonstrated the concept of year-round cultivation of seaweed and automated harvesting. The concept of direct seeding on advanced cultivation substrates with novel binders was proven was proven at sea with improved efficiency and reduced cost of operation. A prototype of an automated harvester was tested and proved the technical feasibility of automated harvesting. Novel seaweed storage bags allowed storing the biomass at sea and ensiling at the same time. The project demonstrated high fermentative yields of fuels from seaweed, and the efficient one-step thermochemical conversions of seaweed to furanics. The engine tests have been set up. The techno-economic and sustainability assessment over the whole value chain showed that the biomass production and harvesting costs are currently too high for fuel applications unless integrated in a cascading biorefinery.

The overall objective of the **MAGNIFICENT** project was 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. The project aims to improve the cultivation of the microalgae by the selection of new, better performing algae varieties, by adaptation of the cultivation process to reach a higher concentration of valuable target products. Algae production is being based on established prototype production protocols at pilot scale. Optimization of the production process (culture medium, energy consumption and thermoregulation) from lab to pilot scale is ongoing. Ingredient production new extraction and purification techniques are developed for the improvement of the extraction and purification processes. In this way the overall aim to maximise the production of compounds of interest can be achieved.

The **MMM-REBIO** project aims to develop mixotrophic cultivation (i.e. the simultaneous use of light and carbon dioxide for photosynthesis and organic carbon for respiration) of diatoms (unicellular eukaryotic algae-microalgae). The MMM-Rebio project aims at using local strains to study and develop mixotrophic or combined method cultivation to maximize growth and outdoor productivity for selected strains on the Swedish west coast for potential industrial use. The focus will be on the bloom-forming coastal diatom Skeletonema marinoi (S. marinoi) whose sequence annotation is ongoing, and the recent knowledge on mixotrophic growth of the model diatom Phaeodactylum tricornutum are employed. The project uses bloom-forming S. marinoi to better understand mixotrophic metabolism, to explore the optimal mixotrophic conditions for enhanced productivity of S. marinoi and to investigate the potential industrial applications of S. marinoi when cultivated under mixotrophy.

The **MONSTAA** project aimed to investigate unique strains of algae and study their metabolism in low temperature bioreactors. Cutting-edge DNA sequencing methods were used to successfully assemble the nuclear, chloroplast and mitochondrial genomes of two novel cold-water microalgae. New cultivation tools consisting of laboratory-scale experimental bioreactors have been developed within this project to study the metabolism, growth and product synthesis of the chosen algae under carefully defined conditions. New cultivation tools consisting of laboratory-scale experimental bioreactors have been developed within this project. These devices help to study the metabolism, growth and product synthesis of the chosen algae under carefully defined conditions. This project uncovered the molecular and physiological mechanisms that allow algae to synthesize a diverse range of valuable metabolites.

The aim of the **SALTGAE** project is to implement and demonstrate at large scale the technological and economic feasibility of an innovative, sustainable and efficient solution for the treatment of high salinity wastewater from the food and drink industry. Generally, combinations of biological and physicochemical methods are used for this kind of wastewater, as the bacterial processes typically used for the elimination of organic matter and nutrients are inhibited under high salinity contents. The solution of SALTGAE consists in the implementation of innovative technologies for each step of the wastewater treatment that will promote energy and resource efficiency, and reduce costs. The use of halotolerant algae/bacteria consortiums for the elimination of organic matter and nutrients wil provide an effective and ecological solution for wastewater treatment, but also it will represent an innovative way of producing algal biomass, that will be valorized into different by-products.

The **SE2B** network deals with the optimisation of the conversion of Solar Energy into Biomass through photosynthetic organisms for producing clean, renewable, sources of energy and fine chemicals. This proposes an interdisciplinary approach including molecular biology, biochemistry, biophysics and biotechnology. Regulation processes at the level of the photosynthetic membranes, integrating molecular processes within individual proteins up to flexible re-arrangements of the membranes, are analysed as a dynamic network of interacting regulations. The aim is to get information about the similarities and differences between cyanobacteria, green algae, diatoms and higher plants, the organisms most commonly employed in biotechnological approaches exploiting photosynthetic organisms, as well as in agriculture. The knowledge gained will be transferred to increase the productivity of algal mass cultures for valuable products, and for the development of sophisticated analytic devices and to the design of synthetic cell factories with efficient light harvesting and energy conversion systems.

VALUEMAG 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 are immobilized onto a soft magnetic conical surface that allows 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. VALUEMAG will demonstrate and scale up the pilot production and harvesting of integrated algae products and bring them nearer to the market in an economically, environmentally and socially sustainable manner. The main objective of the project is to develop an advanced magnetic method for micro-algae cultivation and to utilise this knowledge to produce micro-algaea and to develop economic & viable magnetic Photo-BioReactors for fast growing and easy harvesting of biomass, using the magnetic microalgae and magnetic surface.

4.6 Biorefineries: EU and SET Plan projects

A number of 12 projects have been identified as addressing the research on biorefineries under H2020 RTD EU programme.

BIOFOREVER demonstrates 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. Pilot testing the logistics for the supply of the wood-based feedstocks (spruce, poplar, waste wood) have been set up. Testing of the different feedstocks was conducted in pre-treatment processes, mild-acid pre-treatment and optimizing the process conditions for quality and yield. Process testing have led to first results on suitability of use, yields and product quality impact, followed by tests to purify and upgrade. Simulation models have been prepared for the pre-treatment and application processes for the technical and economic evaluation and comparison of the various value chains (combinations of feedstock, pre-treatment and application).

The **BioMates** project develops and validates an innovative and cost-competitive innovative biomass conversion technologies, including ablative **fast pyrolysis** (AFP) and single-stage mild catalytic **hydroprocessing** (mild-HDT). Fast pyrolysis in-line-catalysis and fine-tuning of BioMates-properties are additional steps to improve the conversion efficiency and cost efficiency of BioMates. Incorporating state-of-the-art hydrogen production from renewable sources and sophisticated electrochemical compression of the hydrogen required as well as optimised energy integration completes the sustainable technical approach. The project aims to develop bio-based intermediates, which can get upgraded in existing oil refineries next to fossil feedstock (co-processing). The project is designed to use only non-food/non-feed material as feedstock.

The **BIOrescue** project aimed to develop and demonstrate a new innovative biorefinery concept based on the cascading use of spent mushroom substrate supplemented by wheat straw and other feedstocks. i.e pruning residues, residual citrus peels and wastes. A wide variety of feedstocks have been analysed to select the best combinations with mushroom compost. An optimal feedstock mixture of compost, wheat, oat and barley straw has been proposed for a mushroom-farm-based biorefinery. A set of thermochemical pretreatment tests have been carried out on mushroom compost alone and in combination with different feedstocks using different catalysts and process conditions. Optimization of the enzymatic hydrolysis conditions has also been carried out.

The general objective of the **BIOSKOH** project is establishing a breakthrough for 2G biorefineries in Europe demonstrating a first of kind sustainable and financially-sound second generation biorefinery. Innovative integrated pre-treatment, hydrolyses and fermentation processes have been developed, tested and demonstrated an in the semi-industrial scale 2G biorefinery plant (Crescentino). This will be upscaled to the 1st of a kind commercial scale Flagship. Biomass was first analytically characterized and then the most promising feedstock were pre-treated and hydrolyzed at continuous pilot plant scale to produce the streams for the enzyme and yeast optimisation carried out. Testing at pilot plant of 5 different crops confirms the feasibility and assesses the potential for optimization. First laboratory experiments dedicated on lignin valorization into materials were performed. A blueprint of the economics sustainability concept and replication scenarios for Europe has been produced, by stimulating the replication of the concept.

The **DEEP PURPLE** project propose a method to transform diluted urban bio-wastes, including mixed waste streams, organic fraction of municipal solid waste (OFMSW), wastewater (WW) and sewage sludge (SS), into feedstock for bio-industry to obtain sustainable bio-products. The use of Purple Phototrophic Bacteria (PPB) ensures the adaption to fluctuating and diluted waste streams to support a stable and profitable production chain as poart of a novel Single-Site Multi-Platform Concept (Biomass, Cellulose and Biogas) to replace current polluting destructive practices with new value added concepts. The first PPB PhotoBiorefinery in the EU will be validated in different environmental, economic, logisticand social scenarios. The concept will be implemented by end-users from four municipalities to transform bio-wastes into high-added value bioproducts:fine chemicals (bio-cosmetics), fertilizers, bio-packaging and self-repairing construction materials.

The **ENGICOIN** project aims at the development of three new microbial factories (MFs), integrated in an organic waste anaerobic digestion platform, based on engineered strains exploiting CO_2 sources and solar radiation or H_2 for the production of value-added chemicals (TRL 3 to TRL 5). This includes: lactic acid from biogas combustion flue gases or CO2 from biogas purification; produce PHA bioplastics from biogas combustion flue gases and carbon from the AD; produce acetone from CO_2 from biogas purification. Synthetic and systems biology studies were performed to increase the CO_2 uptake and selective transformation into the desired products or to facilitate product extraction. At the same time, a new A Proton Exchange Membrane (PEM) electrolyser electrolyser for H_2 production and integration has benn developed and tested.

FIRST2RUN project aimed at demonstrating (TRL 8) the techno, economical and environmental sustainability of a first-of-kind value chain where low input and underutilized oil crops grown in arid and/or marginal lands and not in competition with food or feed, are exploited for the extraction of vegetable oils to be further converted through chemical and biotechnological processes into bio-monomers and esters that will be applied in the formulation of bioproducts. By and co-products from the process will be valorised both for energy, feed for animals and added value chemicals. An optimized low-input protocol for the innovative oil crops cultivation has been set-up and transferred to farmers through specific training sessions. Innovative oilseeds treatment technique was demonstrated allowing to obtain vegetable oils, proteic meal and active molecules. An innovative selective hydrogenation reaction process of vegetable oil have been validated at pilot scale. The lignocellulosic biomass obtained from the cardoon crop has been successfully validated towards the production of bioenergy and cardoon proteic meal has been successfully tested as feed.

GENIALG aimed to demonstrate the economic feasibility and environmental sustainability of cultivating and refining seaweed biomass in 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. The upscaling of current small cultivation seaweed operations to ensure an efficient and mechanised cultivation process that allows for large-scale supply of the quantity range required for biorefinery and provided ensured sufficient high-quality biomass for analysis. The implementation of innovative chemical and biological processes for the extraction of bioactive molecules, hydrocolloids, proteins and minerals for industrial utilization led to the characterization of the composition of algae grown in different locations to assess how this impacts biomass quality and the content of potential value-added products.

IProPBio 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. The project addresses: alternative feedstock and high-value products characterization; thermodynamic data analysis and properties prediction; alternative technological flowsheets for economic and eco-compatible conversion into high value products; mass and energy integration studies to reduce waste; life cycle assessment to determine the net contribution of the best designs to environmental pollution.

MACRO CASCADE aims to prove the concept of the cascading marine macroalgal biorefinery i.e. a production platform that covers the whole technological chain for processing sustainable cultivated macro-algae biomass to high 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. MACRO CASCADE proposes demonstrating large-scale cultivation and harvest at open sea and developing a biorefinery technology platform to convert marine macroalgal biomass to a variety of value added products for industries within food, feed, cosmetics, pharmaceutical and fine chemicals. The approach contributes to the "zero waste society" as the left-over residuals from the biorefinery process can be used for fertilizers and bio-energy.

SABANA 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 and establish processes for bioproducts extraction, process residual biomass to produce biofertilizers and aquafeed in zero-waste schemes. SABANA includes the utilization of microalgae-bacteria consortia and in co-culture with other algae, the implementation of efficient thin-layer cascade and raceway, the scale-up of reactors to ensure stable operation, to recover nutrients from wastewaters, to develop harvesting processes, to establish processes for mild/energy efficient extraction of bioproducts, and to process residual biomass to produce biofertilizers and aquafeed.

TASAB is a novel algal biorefinery concept, offering a closed system integrating thermal and biochemical conversion pathways that maximizes energy production from algae for achieving a net positive energy balance and recycle nutrients. TASAB proposes a novel bio-refinery concept, offering an environmentally-sustainable closed system integrating both anaerobic fermentation processes and pyrolysis to increase energy yield and upgrade bio-oil, while recovering high value products and producing activated carbon from biochar. Macroalgae and two microalgae were selected to be used as feedstock for dark fermentation, anaerobic digestion and pyrolysis. The algae were characterized for their ultimate, proximate and biochemical composition and then used as feedstock for bio-methane and bio-hydrogen production. The products and by products of the processes wee analysed and characterized. TASAB aimed to recover more energy from downstream effluents of the integrated process of anaerobic fermentation and pyrolysis as well as have also succeeded in recovering nutrients.

The **4REFINERY** (SET-Plan flagship) project aims to develop and demonstrate the production of next generation biofuels from more efficient primary liquefaction routes integrated with upgraded downstream (hydro)refining processes. 4REFINERY focuses on optimal pathways for advanced biofuels production through catalytic fast pyrolysis and HTL integrated with upgrading (hydro)refining processes and to bring these technologies from TRL 3-4 to TRL 4-5. The goal is to 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. Mass, energy and elemental balances for the pre-processing steps in fast pyrolysis and hydrothermal liquefaction (HTL) have been retrieved. The two alternative reference bio-oils are being investigated in alternative co-refining steps to establish the basis for selecting the optimal co-refining routes, as determined by the feedstock and end use application. A number of approaches have been evaluated to optimise the efficiency and cost of the primary conversion of the biomass to intermediate bio-oils.

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 €39.3 m.

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, biowaste, 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 (related to the capital and operating costs, conversion efficiency, process reliability), 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 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 or liquefied 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** combustion. 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 however 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, 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, monitoring devices 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** from industrial processes that are suitable for small scale 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 establishing 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.

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.

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.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.

5.1.2.3 Pyrolysis

R&D on pyrolysis focussed on developing **pyrolysis process**, scaling up reactor, improving pyrolysis oil quality. R&D addressed one-step or two-step pyrolysis, catalytic and non-catalysic 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.

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. The greatest challenges yet to address are to develop continuous process operation at high temperatue and especially at high pressure, and to understand the impact of **feedstock composition** and process conditions on **bio-crude quality**.

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 and gasification.

R&D activities addressed 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 progress 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**, 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 and charactersation, 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 varios sources (combustion, anaerobic digestion) and **nutrients** from various waste streams, for the removal of micropollutants and nutrients (nitrogen, phosphorus, etc.). R&D also addressed the improvement of the wastewater treatment process and make wastewater treatment energy positive. While the majority of projects focussed on the use of microalgae, few projects addressed the cultivation, harvesting 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 processes (e.g. ultrasound, hydrolysis 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 forecast

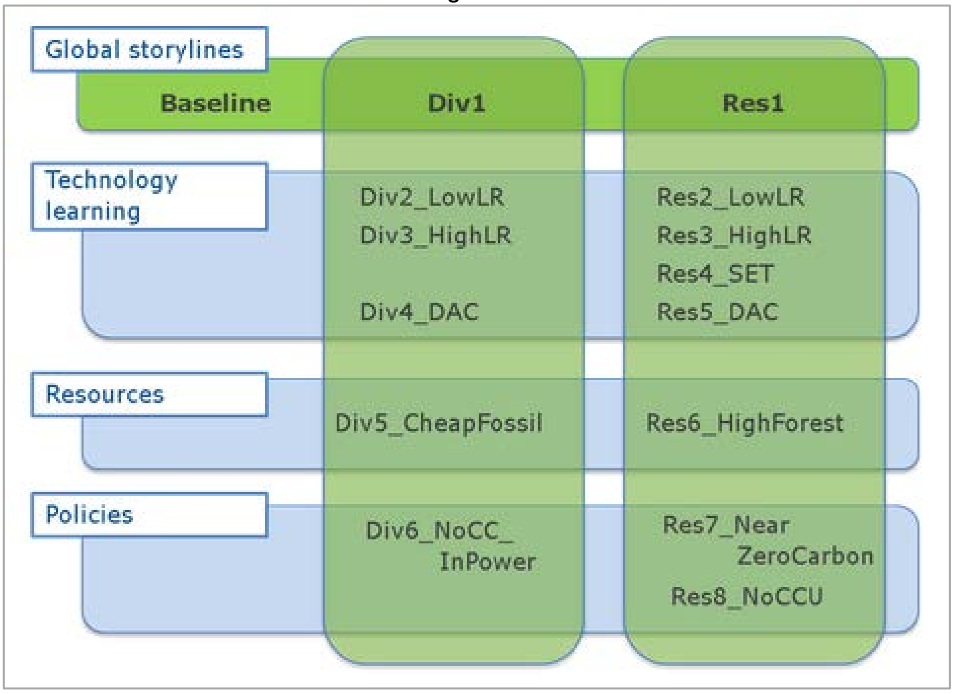
The technology forecasts, based on the JRC-EU-TIMES model (Simoes et al., 2013), has been used for analysing the role of the biomass up to 2050 in the EU energy system for meeting the EU's energy and climate change related policy objectives. The JRC-EU-TIMES depicts possible deployment rates for heat 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. 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.

JRC-EU-TIMES considers the following different crop types, waste and residues sources that can be used heat and power generation: agricultural products, agricultural residues, forestry products, forestry residues, biodegradable fraction of municipal solid waste, agricultural biogas, landfill gas and sewage sludge. Biogas includes methane generated from various biomass feedstocks: gasification of black liquors and woody biomass, as well as decomposition of industrial waste and sludge. Other bioass includes varios waste, black Liquor, industrial wood, municipal waste.

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.

Figure 11. Global Storylines that covers worldwide development of low carbon energy technologies to 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, 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.

In addition to the three main scenarios, a further 13 sensitivity cases were run. Nijs et al. (2018) explains the main features of the model and presents all the scenarios and the overall results. In this technology development report, we focus on the three main scenarios (Baseline, Diversified and Pro-RES) and specific Pro/RE scenarios (Pro-RES SET, Pro-RES: High Forest and Pro-RES NearZeroCarbon), where the targets of the SET Plan are taken into account in the ProRes_SET Plan scenari. For this SET Plan scenario, an overview of the assumptions (on efficiency improvements and cost reductions) for each technology is provided in (Nijs et al., 2018). The SET Plan scenario is considered to give a foresight perspective since the SET Plan targets steer research and innovation, by leading to new or improved technologies at lower costs. The SET Plan scenario considers the same assumption as in the ProRes scenario taking also into account the SET Plan targets in terms of efficiency improvements and cost reductions.

The scenarios were further divided in sensitivity cases by considering different technologies, resources and policies strategies, as illustrated in Figure 11 and Table 9.

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
Pro-RES	REF	-80%	YES	NO	NO	YES
Pro-RES: SET-Plan	SET	-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

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 will grow in the 2020 to 2050 timeframe in all considered scenarios (Figure 12 and Figure 13). Looking more in detail, the modelling results indicate that the installed capacity will increase steadily to reach values around 70-75 GW until 2030, after which the trends for the individual scenarios begin to differ. In fact, it is possible to observe three major trends.

After this period, most of the scenarios indicate a decrease in their capacities, except the Pro-RES NearZeroCarbon, which shows an opposite trend. In 2050, the total installed capacity of biomass plants will reach values between 57 and 105 GW, depending on the analysed scenario.

Thus the Diversified scenario shows a 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 77 GW in 2050. Both Baseline and Pro-RES scenarios scenarios show a decreasing trend after 2030, when they will have capacities around and 77 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.

The Pro-RES SET Plan shows a similar trend with the Pro-RES scenarios with a strong increase until

2030 when the installed capacity reaches 67 GW, decreasing after 2030, to achieve a capacity of 54 GW in 2050 which is the lowest level of all scenarios analysed.

The reason why the Pro-RES scenarios show lower biomass power capacity lies in the competition between this biomass power and other renewables (such are solar and wind) that become cheaper. The use of biomass for heat and power also competes with the production of biofuels for the use in transport that becomes more important for the decabonisation of the transport sector.

In the Pro-RES with Near Zero CO_2 scenario, the installed capacity increases in the period of 2010-2030 when it reaches 68 GW, but increase rapidly in the last simulation period to reach in 2050 a capacity of 105 GW, due to the need to achieve carbon neutrality by 2050 that requires the use of all resources for the achievement of this goal.

Figure 12. Evolution of the installed bioenergy capacity by resources in different scenarios of JRC-EU-TIMES simulations

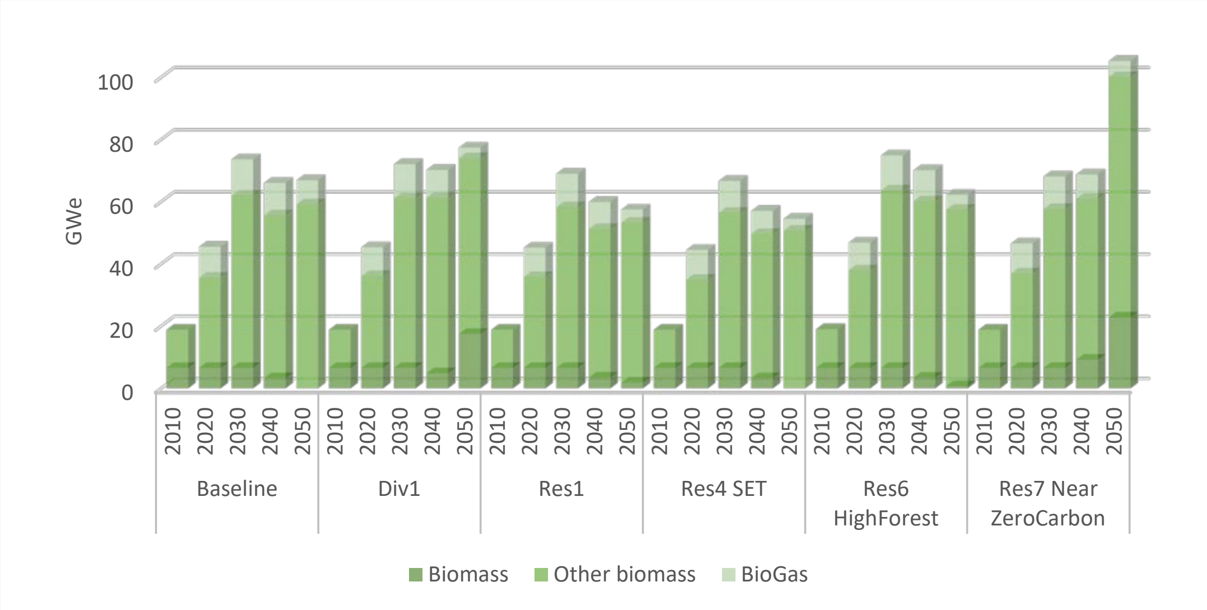
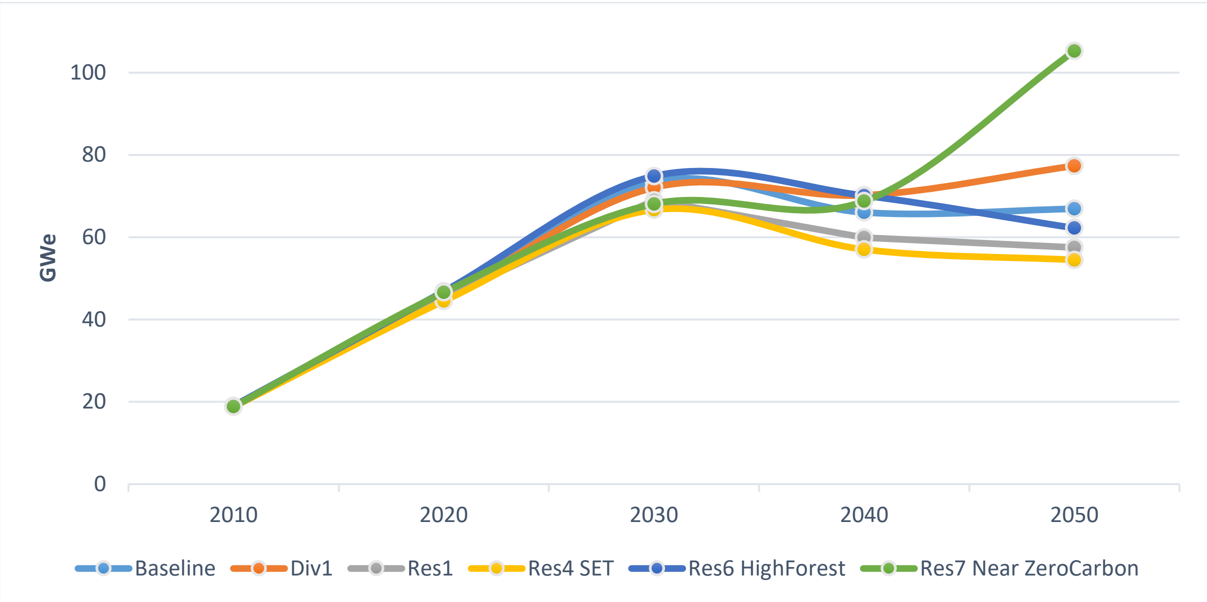


Figure 13. Evolution of the installed bioenergy capacity in different scenarios of JRC-EU-TIMES simulations



The analysis of the electricity production from bioenergy plants (Figure 14 and Figure 15) shows similar trends with the installed capacity simulations. All the different scenarios show growth trends until 2030, when they will reach production values between 228 and 280 TWh. The period of 2030-2040 will not see significate changes of the trends in different scenarios. The different Pro RES scenarios show a decrease in electricity production from biomass, except for the Pro-RES Near Zero CO_2 scenario where electricity production will continue to increase until 2050, to reach about 367 TW in 2050. The Pro RES SET scenario shows the lowest levels of electricity production in comparison to all other scenarios, including Baseline and Diversified scenarios.

Figure 14. Evolution of bioelectricity production by resources in different scenarios of JRC-EU-TIMES simulations

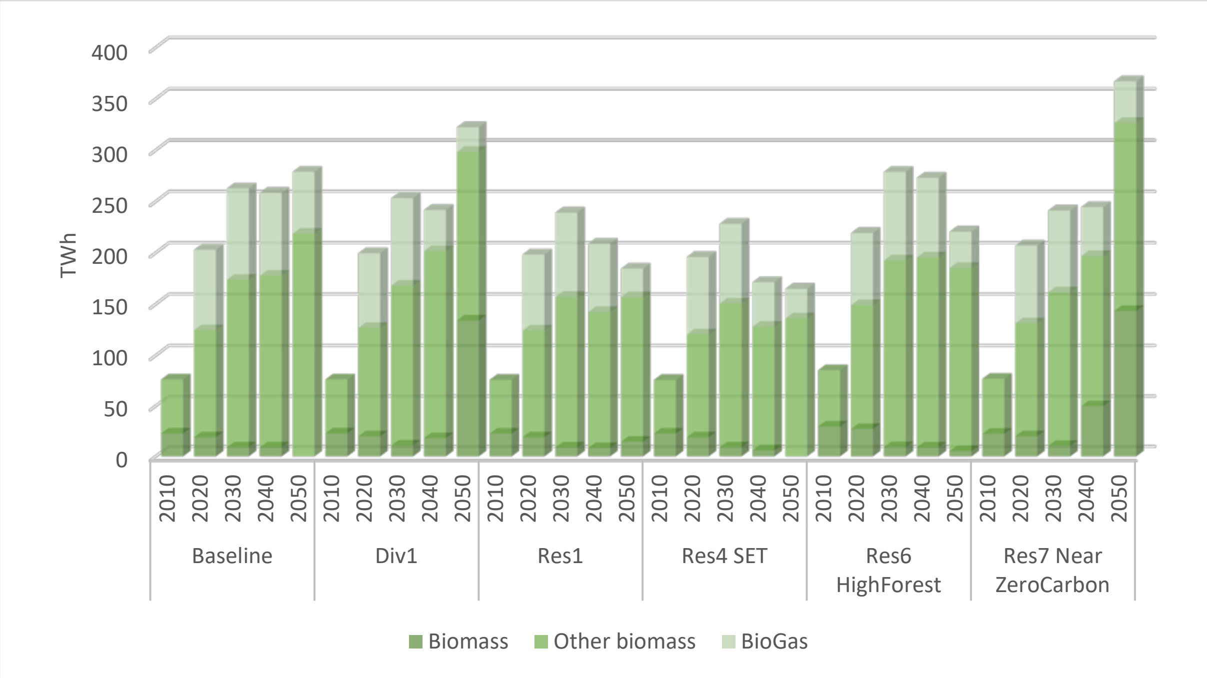
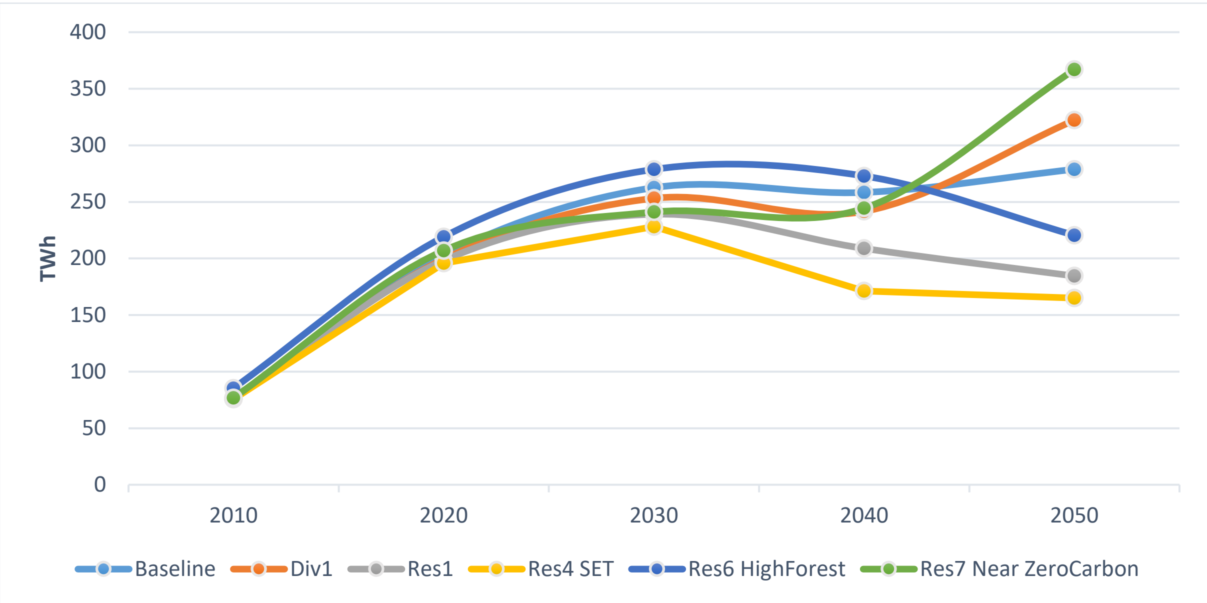


Figure 15. Evolution of bioelecticity production in different scenarios of JRC-EU-TIMES simulations



The reason why the Pro-RES scenarios show lower electricity production is, as explained above, that biomass electricity production competes with other renewables (such as solar and wind) that become cheaper on longer term. The production of electricity from biomass also competes with the production of biofuels for the use in transport that becomes more important for the decabonisation of the transport sector.

The JRC-EU-Times model projections show that the use of biomass for bioenergy production will increase to a small extent, to reach about 7000 PJ until 2050 (Figure 16 and Figure 17) considering the fact that the use of biomass in 2017 was about 6000 PJ.

Figure 16. Evolution of the primary energy production by resources in different scenarios of JRC-EU-TIMES simulations

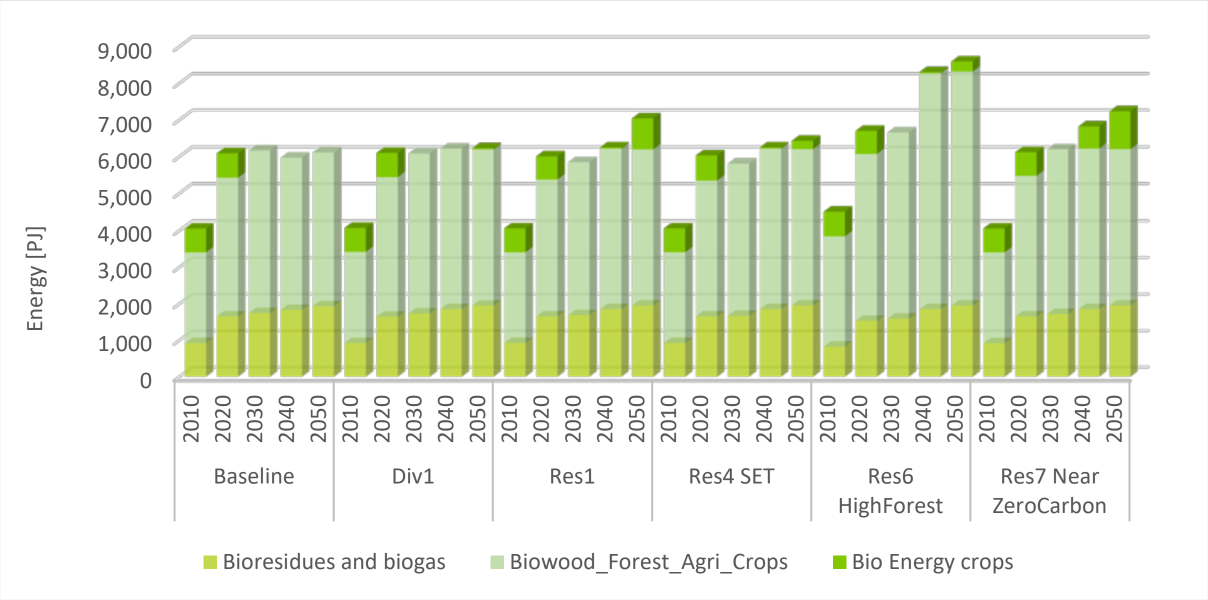
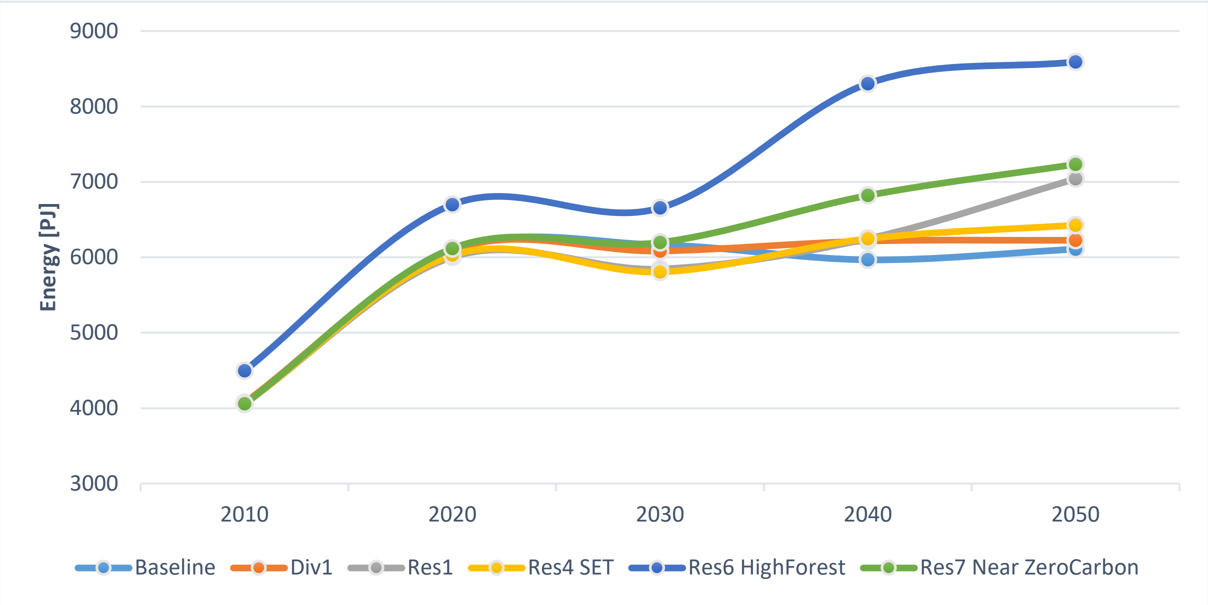


Figure 17. Evolution of the total of primary energy production in different scenarios of JRC-EU-TIMES simulations



The Pro-RES Near Zero CO_2 and the Pro-RES scenarios estimate the production of 7000 PJ of primary energy in 2050, while the Baseline and The Pro-RES SET scenario provides the lowest value for the primary energy production from biomass of all Pro RES scenarios, in relation to the high competition of bioenergy with other renewables. Baseline and Diversified scenarios suggest the production of 6000 PJ in the same period, due to the lack of incentives to reach higher use of biomass for energy generation. In these scenarios, most of the biomass resources will come from forest and agro systems, followed by bioresidues / biogas resources, and to little extend by energy crops. The Pro RES High scenario estimates a significantly higher level of bioenergy, of about 8600 PJ, due to the higher potentials of biomass for energy uses, derived from the need to prioritise the use of biomass for energy purposes.

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, lignocellulosic feedstocks (agri-residues, straw, organic fraction of municipal solid waste 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 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), 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, 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 lifetimes 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 challenges yet to be addressed are to achieve continuous process operation and to understand the impact 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 TRL 6-7. 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). 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 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

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Annex 1. Cross-cutting bioenergy projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
AfriVeg	746347	Assessment of African Vegetation Resources: New Perspectives from Satellite Passive Microwave Datasets	185,857	185,857	2018-01-01	2019-12-31
AgRefine	860477	A Disruptive Innovative Cooperative Entrepreneurial (DICE) education, training and skills development programme rolling out the next generation of Agri Biorefinery and Valorisation Bioeconomy leaders	4,038,685	4,038,685	2019-10-01	2023-09-30
AGRIFORVALOR	696394	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
AgroCycle	690142	Sustainable techno-economic solutions for the agricultural value chain	7,650,050	6,960,294	2016-06-01	2019-05-31
AGROinLOG	727961	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
AgroPellet	672615	Development of a pelletising machine to process multiple-source agricultural mixes	71,429	50,000	2015-05-01	2015-10-31
ALTERFOR	676754	Alternative models and robust decision-making for future forest management	3,997,367	3,997,367	2016-04-01	2020-09-30
Ambition	731263	Advanced biofuel production with energy system integration	2,494,986	2,494,986	2016-12-01	2019-11-30
Amicrex	661198	Development of a Microwave Assisted Cell Disruption of Biomass and Extraction of Valuable Compounds	171,461	171,461	2015-05-01	2020-01-28
BESTF3	691637	Bioenergy Sustaining the Future (BESTF) 3	6,477,369	2,137,532	2016-01-01	2020-12-31
BestRES	691689	Best practices and implementation of innovative business models for Renewable Energy aggregatorS	1,994,813	1,994,813	2016-03-01	2019-02-28
BIAR	807140	THE BiAR PROCESS: TRANSFORMING LOW-VALUE BIOMASSESINTO HIGHLY VALUABLE FOR ENERGY-RECOVERY FUELS	71,429	50,000	2018-03-01	2018-06-30
BilletPro	663811	Development of a harvesting machine for short rotation plantations for the production of billets with advantageous properties in terms of handling, drying and storing	71,429	50,000	2015-03-01	2015-08-31
Bioenergy4Business	646495	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
BioEnergyTrain	656760	BioEnergyTrain	3,697,580	3,697,579	2015-05-01	2019-04-30
BIOFIT	817999	Bioenergy retrofits for Europe's industry	2,626,238	2,626,238	2018-10-01	2021-09-30
Biomasud Plus	691763	Developing the sustainable market of residential Mediterranean solid biofuels.	1,971,610	1,971,610	2016-01-01	2018-12-31
BioPellets	735279	Integrating food waste into wood pellets to convert waste grease to a useful biofuel.	71,429	50,000	2016-08-01	2016-11-30

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
BIOPLAT-EU	818083	Promoting sustainable use of underutilized lands for bioenergy production through a web-based Platform for Europe	2,490,408	2,490,408	2018-11-01	2021-10-31
BioReg	727958	Absorbing the Potential of Wood Waste in EU Regions and Industrial Bio-based Ecosystems	996,056	996,056	2017-01-01	2019-12-31
BioRES	645994	Sustainable Regional Supply Chains for Woody Bioenergy	1,865,411	1,865,411	2015-01-01	2017-06-30
BIOSURF	646533	BIOmethane as SUstainable and Renewable Fuel	1,872,912	1,872,912	2015-01-01	2017-12-31
BioValue	666644	Quality determination of solid biofuels in real time	2,335,550	1,634,885	2015-03-01	2018-05-31
BioVill	691661	Bioenergy Villages (BioVill) - Increasing the Market Uptake of Sustainable Bioenergy	1,998,918	1,998,918	2016-03-01	2019-02-28
CarbonOrO	729834	CarbonOrO	71,429	50,000	2016-05-01	2016-09-30
CarboPlex	661323	Development of carbon-rich biochar-mineral complexes for soil amendment, carbon sequestration and beyond (CarboPlex)	183,455	183,455	2015-04-01	2017-03-31
CargoMill	711602	The CARGOMIL, an innovative self propelled all terrain vehicle for mobilising "where and when the biomass is".	71,429	50,000	2015-12-01	2016-05-31
COREGAL	641585	Combined Positioning-Reflectometry Galileo Code Receiver for Forest Management	1,314,249	906,268	2015-01-01	2017-05-31
COSYNAT	674065	Clean, Versatile and Cost-effective Waste-to-Energy Solution	71,429	50,000	2015-05-01	2015-08-31
DEPURGAN	673771	Swine-farm revolution	2,702,033	1,890,110	2015-09-01	2017-09-30
DIABOLO	633464	Distributed, integrated and harmonised forest information for bioeconomy outlooks	4,998,970	4,734,595	2015-03-01	2019-02-28
DiBiCoo	857804	Digital Global Biogas Cooperation	2,998,181	2,998,181	2019-10-01	2022-06-30
DRALOD	820554	Renewables-based drying technology for cost-effective valorisation of waste from the food processing industry	2,468,153	1,906,892	2018-08-01	2020-12-31
EcoBioMass	768291	EcoBioMass – harvesting forest energy biomass in the 21st century	1,856,500	1,299,550	2017-08-01	2019-07-31
EFFORTE	720712	Efficient forestry by precision planning and management for sustainable environment and cost-competitive bio-based industry	4,203,421	2,230,221	2016-09-01	2019-08-31
ENABLING	774578	Enhance New Approaches in BioBased Local Innovation Networks for Growth	1,997,640	1,997,640	2017-12-01	2020-11-30
Enerbox	684901	Sustainable and Standalone Oxyhydrogen powered heat generator box	71,429	50,000	2015-06-01	2015-09-30
ENERCOVERY	712022	Modular green-energy recovery and business model	71,429	50,000	2015-12-01	2016-04-30
ERIFORE	654371	Research Infrastructure for Circular Forest Bioeconomy	2,630,950	2,628,700	2016-01-01	2018-01-31
ETIP Bioenergy-SABS	727509	European Technology and Innovation Platform Bioenergy – Support of Advanced Bioenergy Stakeholders 2016 - 17	599,105	599,105	2016-09-01	2018-08-31
ETIP-B-SABS 2	825179	European Technology and Innovation Platform Bioenergy - Support of			2018-09-01	2021-08-31

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
		Renewable Fuels and Advanced Bioenergy Stakeholders 2	997,720	997,720		
EUWaste	719028	Ecological Utilization of Waste	71,429	50,000	2016-03-01	2016-08-31
FACCE SURPLUS	652615	SUstainable and Resilient agriculture for food and non-food systems	15,151,515	5,000,000	2015-03-01	2020-02-29
FLEXYNETS	649820	Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS	1,999,364	1,999,364	2015-07-01	2018-12-31
FORBIO	691846	Fostering Sustainable Feedstock Production for Advanced Biofuels on underutilised land in Europe	1,941,581	1,941,581	2016-01-01	2018-12-31
GasFermTEC	810755	GasFermTEC: Gas Fermentation Technologies ERA Chair	2,496,875	2,496,875	2018-09-01	2023-08-31
GRACE	745012	GRowing Advanced industrial Crops on marginal lands for biorEfineries	15,000,851	12,324,633	2017-06-01	2022-05-31
GreenCarbon	721991	Advanced Carbon Materials from Biowaste: Sustainable Pathways to Drive Innovative Green Technologies	3,623,224	3,623,224	2016-10-01	2020-09-30
greenGain	646443	Supporting Sustainable Energy Production from Biomass from Landscape Conservation and Maintenance Work	1,829,391	1,829,391	2015-01-01	2017-12-31
GRIDSOL	727362	SMART RENEWABLE HUBS FOR FLEXIBLE GENERATION: SOLAR GRID STABILITY	3,421,448	3,421,448	2016-10-01	2019-11-30
HarvPell	763303	Upscale and redesign of a mobile harvesting and pelletizing disruptive all-in-one machine	71,429	50,000	2017-03-01	2017-06-30
Hybrid-BioVGE	818012	Hybrid Variable Geometry Ejector Cooling and Heating System for Buildings Driven by Solar and Biomass Heat	3,701,858	3,362,670	2019-06-01	2022-05-31
ICT-BIOCHAIN	792221	ICT-BIOCHAIN - ICT Tools in Efficient Biomass Supply Chains for Sustainable Chemical Production	999,668	949,685	2018-06-01	2020-05-31
iMETland	642190	iMETland: A new generation of Microbial Electrochemical Wetland for effective decentralized wastewater treatment	3,461,623	2,924,810	2015-09-01	2018-12-31
InBPSOC	839806	Increases biomass production and soil organic carbon stocks with innovative cropping systems under climate change	219,312	219,312	2020-02-01	2022-01-31
ISAAC	691875	Increasing Social Awarness and ACceptance of biogas and biomethane	1,480,535	1,480,535	2016-01-01	2018-06-30
ISABEL	691752	Triggering Sustainable Biogas Energy Communities through Social Innovation	1,897,438	1,897,438	2016-01-01	2018-12-31
KeepWarm	784966	Improving the performance of district heating systems in Central and East Europe	2,098,498	2,098,489	2018-04-01	2020-09-30
LIBBIO	720726	Lupinus mutabilis for Increased Biomass from marginal lands and value for BIOrefineries	4,923,750	4,923,750	2016-10-01	2020-09-30
MAGIC	727698	Marginal lands for Growing Industrial Crops: Turning a burden into an opportunity	5,999,988	5,999,988	2017-07-01	2021-06-30
MOBILE FLIP	637020	Mobile and Flexible Industrial Processing of Biomass	9,698,843	8,606,175	2015-01-01	2018-12-31
MOVARC	817389	Modified Vacuum Rankine Cycle	71,429	50,000	2018-06-01	2018-11-30
MUSIC	857806	Market Uptake Support for Intermediate Bioenergy Carriers	2,999,871	2,999,871	2019-09-01	2022-08-31

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
NewCat4Bio	751774	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
NoAW	688338	Innovative approaches to turn agricultural waste into ecological and economic assets	7,816,233	6,887,570	2016-10-01	2020-09-30
OPTIFUEL	733664	Smart and reliable solid biofuel quality control solution	1,699,055	1,189,339	2016-10-01	2018-12-31
PELLETON	710454	PELLETON – a device for production of pellets from biomass and agricultural waste for energy purposes	71,429	50,000	2015-12-01	2016-05-31
progRESsHEAT	646573	Supporting the progress of renewable energies for heating and cooling in the EU on a local level	1,728,306	1,728,305	2015-03-01	2017-10-31
PROMETHEUS-5	733099	Energy efficient and environmentally friendly multi-fuel power system with CHP capability, for stand-alone applications.	1,731,996	1,212,397	2016-09-01	2019-04-30
Proxipel	882623	Mobile pelletizing unit	71,429	50,000	2019-12-01	2020-05-31
REGATRACE	857796	REnewable GAs TRAde Centre in Europe	3,000,488	3,000,485	2019-06-01	2022-05-31
Res2Pel	661852	Innovative treatment process for biogenic waste and residual materials to manufacture compactedfuels as pellets or briquettes	71,429	50,000	2015-02-01	2015-07-31
ROBIOT	782319	Improving the sustainability of bioenergy production with a Robot for Biomass Quality Management	71,429	50,000	2017-08-01	2018-01-31
SECURECHAIN	646457	Securing future-proof environmentally compatible bioenergy chains	1,809,586	1,809,586	2015-04-01	2018-07-31
SEEMLA	691874	Sustainable exploitation of biomass for bioenergy from marginal lands in Europe	1,629,884	1,629,884	2016-01-01	2018-12-31
SE-SBR	800419	Sorbent-enhanced Steam Biomass Reforming for Integrated Bio-energy with Carbon Capture and Storage	187,420	187,420	2018-10-01	2020-09-30
SmartGasGrid	867921	Enabling large-scale injection of biomethane in the European gas distribution	71,429	50,000	2019-06-01	2019-09-30
SolBio-Rev	814945	Solar-Biomass Reversible energy system for covering a large share of energy needs in buildings	4,790,536	4,790,536	2019-05-01	2023-04-30
STOREandGO	691797	Innovative large-scale energy STOragE technologies AND Power-to-Gas concepts after Optimisation	27,973,370	17,937,359	2016-03-01	2020-02-29
uP_running	691748	Take-off for sustainable supply of woody biomass from agrarian pruning and plantation removal	1,992,920.00	1,992,920.00	2016-04-01	2019-06-30

Annex 2. Anaerobic digestion projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
ABWET	643071	Advanced Biological Waste-to-Energy Technologies	3,918,951	3,918,951	2015-01-01	2018-12-31
ADD-ON	666427	A demonstration plant of enhanced biogas production with Add-On technology	2,021,078	1,414,754	2015-03-01	2019-10-31
AMBIENCE	827586	disruptive capturing and revalorisation system of AMmonia for BIogas plants ENhancing Circular Economy	71,429	50,000	2018-08-01	2019-01-31
ANAERGY	858805	Advanced Multistage Sequential Wastewater Treatment Technology	1,748,750	1,224,125	2019-06-01	2021-05-31
AnBIOSST	798901	Anaerobic Biotechnology for Sewage Sludge Treatment: Integrating Anaerobic Bioleaching with Anaerobic Digestion	172,800	172,800	2018-06-18	2020-06-17
Bin2Grid	646560	Turning unexploited food waste into biomethane supplied through local filling stations network	709,469	709,468	2015-01-01	2017-12-31
BIOFERLUDAN	652017	BIOFERLUDAN: COST-EFFECTIVE HUMIC FERTILIZERS TROUGH DIGESTATE TREATMENT AT INDUSTRIAL BIOGAS PLANT	71,429	50,000	2014-10-01	2015-03-31
Biofrigas	762442	Turning manure into fuel: a container based LBG plant for small to medium scale farms	71,429	50,000	2017-02-01	2017-04-30
BioFuel Fab	882510	Biogas production from non-food lignocellulosic biomass waste.	71,429	50,000	2019-12-01	2020-05-31
Biogas2Syngas	846255	Rational Design for Coke-resistant Dry Reforming Catalyst using Combined Theory and Operando Raman Experiments	171,473	171,473	2019-11-01	2021-10-31
BiogasAction	691755	BiogasAction: Promotion of sustainable biogas production in EU	1,999,885	1,999,885	2016-01-01	2018-12-31
BIOGASTIGER	783727	BIOGASTIGER® system – turning global organic waste streams into smart and clean energy	3,043,375	2,130,363	2017-11-01	2019-10-31
BIOGRAPHENE	877210	Producing graphene from biogas: an innovative, renewable and cost-effective value-chain for industrialising the material of the future	71,429	50,000	2019-08-01	2020-01-31
bionic agitator	673676	Feasibility study of a bionic agitator – a prototype of this agitator has shown great potential for energy reduction of agitator technology.	71,429	50,000	2015-05-01	2016-04-30
BIONICO	671459	BIOgas membrane reformer for deceNtralIzed hydrogen produCtiOn	3,396,640	3,147,640	42248	43830
BIOO Panel	767678	Green Electricity from plants' photosynthesis	1,817,826	1,272,478	2017-07-01	2019-06-30
BioRECO2VER	760431	Biological routes for CO2 conversion into chemical building blocks	7,239,149	6,812,188	2018-01-01	2021-12-31
BIORELOAD	774980	INNOVATIVE BIOLOGICAL PRE-TREATMENT TO INCREASE THE METHANE YIELD OF LIGNOCELLULOSIC AGRO-INDUSTRIAL WASTE IN BIOGAS PLANTS	71,429	50,000	2017-05-01	2017-08-31
BIOROBURplus	736272	Advanced direct biogas fuel processor for robust and cost-effective decentralised hydrogenproduction	3,813,536	2,996,249	2017-01-01	2020-06-30
biowave	691404	Upscale and demonstration of a integrated novel microwave pre-treatment system for efficient production of biogas from anaerobic digestion of pig manure to create a sustainable waste management system	1,948,920	1,364,244	2016-04-01	2018-07-31

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
BPV	672434	EXTRACTING VALUE FROM BYPRODUCTS OF THE FOOD INDUSTRY	71,429	50,000	2015-05-01	2015-08-31
CoMeth	876682	BREAKTHROUGH METHANATION TECHNOLOGY FOR ANY SOURCE OF CO2/CO	71,429	50,000	2019-08-01	2019-11-30
DECISIVE	689229	A DECentralIzed management Scheme for Innovative Valorization of urban biowastE	8,713,971	7,755,102	2016-09-01	2020-08-31
DEMETER	720714	Demonstrating more efficient enzyme production to increase biogas yields	6,539,558	4,629,586	2016-08-01	2020-01-31
DEMOSOFC	671470	DEMOnstration of large SOFC system fed with biogas from WWTP	5,905,336	4,492,561	2015-09-01	2020-08-31
DIET	797259	Direct Interspecies Electron Transfer in advanced anaerobic digestion system for gaseous transport biofuel production	187,866	187,866	2018-05-01	2020-04-30
DualMetha	827977	A cost-effective process for methanisation of unexploited agricultural waste.	71,429	50,000	2018-09-01	2018-12-31
FimusKraft	882691	Biotechnological production of energy by electrification of biowaste	71,429	50,000	2019-11-01	2020-02-29
FLEXBIO	789916	FLEXBIO – an innovative process for the decentralised treatment of organically contaminated wastewater with reduced energy requirements, CO2 emissions and operating costs	71,429	50,000	2017-12-01	2018-05-31
GASFARM	734959	SMALL-SCALE ANAEROBIC DIGESTION FOR AFFORDABLE, EFFICIENT AND SUSTAINABLE MANAGEMENT OF FARMS WASTE	71,429	50,000	2016-09-01	2016-12-31
H2AD-aFDPI	698374	H2AD - Innovative and scalable biotechnology using Microbial Fuel Cell and Anaerobic Digestion for the treatment of micro-scale industrial and agriculture effluents to recover energy from waste	3,054,206	2,137,944	2015-11-01	2017-10-31
HOMEBIOGAS	777770	Turning food industry's organic wastw into value	2,292,500	1,604,750	2017-08-01	2020-01-31
INCOVER	689242	Innovative Eco-Technologies for Resource Recovery from Wastewater	8,432,456	7,209,032	2016-06-01	2019-07-31
KATEDRAL	807723	An Eco-Friendly and Sustainable Sewage Sludge Valorization Unit	71,429	50,000	2018-03-01	2018-06-30
KUDURA	763094	Upscaling of a portable hybrid solution for power supply, smart waste-to-energy	71,429	50,000	2017-02-01	2017-05-31
Lt-AD	718212	Low-temperature Anaerobic Digestion treatment of low-strength wastewaters	2,418,815	1,693,171	2016-06-01	2018-05-31
MUBIC	778065	Mushroom and biogas production in a circular economy	5,466,533	2,499,999	2017-08-01	2020-01-31
Multi-AD Feasibility	808774	High performance MULTIphase Anaerobic Digester for agroindustrial wastewater treatment	71,429	50,000	2018-01-01	2018-04-30
NOMAD	863000	Novel Organic recovery using Mobile ADvanced technology	5,499,857	4,250,477	2019-10-01	2022-09-30
NTPleasure	748196	Non-Thermal PLasma Enabled cAtalysis-Separation system for UpgRading biogasto mEthane-NTPleasure	195,455	195,455	2018-01-15	2020-01-14
OptiMADMix	658855	Optimized Mesophilic Anaerobic Digestion Mixing	183,455	183,455	2016-01-05	2018-01-04
PHARM AD	661427	Removal of pharmaceutical micro-pollutants from waste water by			1 August 2015	31 July 2017

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
		anaerobic digestion and its effect on nitrogen recovery from digestate by micro-algae	183,455	183,455		
Poul-AR	652171	Poultry manure valorization	71,429	50,000	2014-10-01	2015-03-31
POWERSTEP	641661	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
Record Biomap	691911	Research Coordination for a Low-Cost Biomethane Production at Small and Medium Scale Applications	499,922	499,921	2016-04-01	2018-09-30
RGH2 OSOD system	774512	OSOD - 1 step process hydrogen generator for highly efficient, safe and cost competitive production and storage of hydrogen	71,429	50,000	2017-06-01	2017-11-30
SHEPHERD	731695	Energy-Efficient Activated Sludge Monitoring for Wastewater Treatment Plants	2,508,750	1,756,125	2016-08-01	2018-07-31
SYSTEMIC	730400	Systemic large scale eco-innovation to advance circular economy and mineral recovery from organic waste in Europe	9,723,586	7,859,829	2017-06-01	2021-05-31
UBI	886415	Biological Integral Biogas Upgrading	71,429	50,000	2019-12-01	2020-04-30
UltraBio	761513	Recovery of nutrients from agricultural residues and improved dewatering through ultrasound technology	71,429	50,000	2017-02-01	2017-07-31
VegWaMus CirCrop	751052	Developing commercial mushroom and vegetable production in an integrated food to waste to food biosystem.	196,400	196,400	2017-10-01	2021-11-25
VicInAqua	689427	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
WASTE2WATTS	826234	Unlocking unused bio-WASTE resources with loW cost cleAning and Thermal inTegration with Solid oxide fuel cells	1,681,603	1,681,603	2019-01-01	2020-12-31
ZeoBio-NG	728883	Innovative biogas upgrading system based on novel Zeolite adsorbent technology for producing Bio-based Natural Gas	71,429	50,000	2016-06-01	2016-11-30

Annex 3. Biomass combustion projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
AgroBioHeat	818369	Promoting the penetration of agrobiomass heating in European rural areas	2,998,044	2,998,044	2019-01-01	2021-12-31
ARBAHEAT	818349	Cost-effective transformation of a Highly-Efficient, Advanced, Thermal Ultra-SuperCritical coal-fired power plant into a CHP by retrofitting and integrating an ARBAFLAME biomass upgrading process.	26,022,635	19,262,648	2018-10-01	2022-09-30
BELENUS	815147	Lowering Costs by Improving Efficiencies in Biomass Fueled Boilers: New Materials and Coatings to Reduce Corrosion	4,991,324	4,991,324	2019-03-01	2023-02-28
BioBur	808747	Multifuel, Economic, High Efficiency High Thermal Power Rotating Biomass Burner for IndustrialApplications	71,429	50,000	2018-02-01	2018-05-31
bioburner	728290	Sustainable Hybrid Dual Burner	71,429	50,000	2016-06-01	2016-09-30
Biofficiency	727616	Highly-efficient biomass CHP plants by handling ash-related problems	4,603,760	4,603,760	2016-11-01	2019-10-31
Bio-HyPP	641073	Biogas-fired Combined Hybrid Heat and Power Plant	5,775,869	5,775,869	2015-06-01	2019-12-31
C-HEAT	738569	Condensed Heat - Optimization and scaling up of an energy efficient, long-during biomass condensation boiler with curved heat exchanger	2,012,650	1,408,855	2016-09-01	2018-11-30
CHP	662195	Upscaling and commercialization of a highly efficient wood pellets fired steam engine CHP for heat and power generation	71,429	50,000	2015-01-01	2015-05-31
cleanFIRE	866595	The first pellet stove with ultra-precise air supply that reduces to near-zero the harmful emissions produced during single room heating	71,429	50,000	2019-05-01	2019-08-31
CYCLOMB	760551	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
DEBS	811529	Significantly cheaper and cleaner energy from biomass combustion	3,412,625	2,388,838	2018-07-1	2020-12-31
DEBS	735368	Dall Energy Biomass System	71,429	50,000	2016-08-01	2016-10-31
DeReco	651441	Feasibility Study on Decentralised Heat Recovery	71,429	50,000	2014-10-01	2015-02-28
DT4BIOMASS	861842	Digital twin for biomass boilers	75,500	75,500	2019-12-15	2020-12-14
ECOVAPOR	730790	Cost-effective High-efficiency Smart Steam Boiler of Low Emission technology	1,991,926	1,425,098	2016-10-01	2018-09-30
FLORIAN	761812	AUTOMATIC REGULATION OF COMBUSTION PROCESS FOR WOOD STOVES AND FIREPLACES	71,429	50,000	2017-02-01	2017-05-31
Heat2Energy	672421	Demonstrating a highly-efficient and cost-effective energy conversion technology for waste heat recovery	71,429	50,000	2015-05-01	2015-09-30
HPC4E	689772	HPC for Energy	1,998,176	1,998,176	2015-12-01	2017-11-30
HyBurn	682383	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
HyBurn	671950	New high temperature in-situ premix gas combustion systems for		50,000	2015-06-01	2015-11-30

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
		more efficient and cleaner combustion of hydrogen and lean gases	71,429			
IE-E	728284	Innovative heat-to-power engine for very low temperature heat recovery applications	71,429	50,000	2016-07-01	2016-12-31
INSERTRONIC	711324	Development of highly-efficient low-emission log wood-fired closed fireplace INSERts thanks to an automated elecTRONIC control system	1,691,400	1,183,980	2016-02-01	2018-01-31
Laelia Due	775051	A smart pellet stove that combines efficient heat generation with IoT	71,429	50,000	2017-04-01	2017-07-31
MILESTONE	695747	Multi-Scale Description of Non-Universal Behavior in Turbulent Combustion	2,499,884	2,499,884	2016-06-01	2021-05-31
NanoORC	704201	Nanofluids as working fluids for organic Rankine cycles	200,195	200,195	1 March 2017	28 February 2020
ORC-PLUS	657690	Organic Rankine Cycle - Prototype Link to Unit Storage	7,297,149	6,249,316	2015-05-01	2019-10-31
POWERICE	745062	Organic Rankine Cycle Cogeneration Plant of one-farm size using rice straw as single fuel	71,429	50,000	2017-01-01	2017-03-31
PyroTRACH	726165	Pyrogenic TRansformations Affecting Climate and Health	1,999,832	1,999,832	2017-06-01	2022-05-31
RECaPHOS	842138	Development of an innovative sustainable process for simultaneous sewage sludge fluidized bed combustion and REcovery of PHOsphorus in a Ca bed	262,210	262,210	2019-05-15	2022-05-14
SINTRAN	651475	Safe and INtegrated thermal TRANsformation of humid organic waste resulting in green energy and valuable remainders	71,429	50,000	2014-11-01	2015-04-30
TASIO	637189	Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries	3,989,248	3,989,248	41974	43616
The Exergyn Drive	672528	THE EXERGYN DRIVE™ – AN ENGINE THAT RUNS ON HOT WATER	3,547,219	2,483,053	2015-06-01	2017-05-31
TUCLA	669466	Towards a deepened understanding of combustion processes using advanced laser diagnostics	2,442,000	2,442,000	2016-01-01	2020-12-31
USELA	663057	Useful energy from contaminated landfill gas	71,429	50,000	2014-12-01	2015-02-28
VADEMECOM	714605	VAlidation driven DEvelopment of Modern and Efficient COMbustion technologies	1,499,110	1,499,110	2017-04-01	2022-03-31

Annex 4. Biomass torrefaction projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
SteamBio	636865	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
TOPIS-BioCirc	843723	Integrating torrefaction of pulp and paper industry sludge with microbial conversion: A new approach to produce bioenergy carriers and biochemicals in a view of bio and circular economy.	154,193	154,193	2020-09-01	2022-08-31
Torero	745810	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	Project name	Overall Budget	EU Funding	Start	End
Bio4Products	723070	4x4, demonstrating a flexible value chain to utilize biomass functionalities in the processing industry	5,930,520	4,201,502	2016-09-01	2020-08-31
ECOCAT	752941	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
FLEXI-PYROCAT	643322	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
Hydrogreen	836514	Towards local circular economy: biomass-based pyrogasification process for the production of green hydrogen	71,429	50,000	2018-11-01	2019-02-28
Pirocrack	817214	Integrated pyrolisis and thermal cracking technology to revolutionise the MSW treatment market	71,429	50,000	2018-06-01	2018-09-30
PYROCHEM	656967	Biopolymers 13C tracking during fast pyrolysis of biomass-A 2-level mechanistic investigation	183,455	183,455	2015-10-01	2017-09-30
PYROTECH	836243	Climate Positive Drying System for Coffee Industries using a highly disruptive Pyrolysis Technology	71,429	50,000	2018-12-01	2019-03-31
Residue2Heat	654650	Renewable residential heating with fast pyrolysis bio-oil	5,466,479	5,465,728	2016-01-01	2019-12-31
SmartCHP	815259	Smart and flexible heat and power from biomass derived liquids for small-scale CHP application	4,042,455	4,042,455	2019-06-01	2023-05-31

Annex 6. Hydrothermal processing projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
HTC4WASTE	684143	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
HTCycle	823124	Sewage sludge reuse with Phosphate recovery and heavy metal absorption with an innovative HTC technology.	1,962,000	1,373,400	2018-09-01	2020-08-31
HTSew	651425	Use of HTC technology as an innovative reuse method for sewage sludge	71,429	50,000	2014-10-01	2015-03-31
Hydrofaction	666712	Resource and Cost Effective Conversion of Biomass to HydrocarbonTM Oil	2,631,166	1,841,816	2015-04-01	2017-03-31
HyFlexFuel	764734	Hydrothermal liquefaction: Enhanced performance and feedstock flexibility for efficient biofuel production	5,038,344	5,038,344	2017-10-01	2021-09-30
NextGenRoadFuels	818413	Sustainable Drop-In Transport fuels from Hydrothermal Liquefaction of Low Value Urban Feedstocks	5,074,876	5,074,876	2018-11-01	2022-10-31
REBOOT	849841	Resource efficient bio-chemical production and waste treatment	1,494,622	1,494,622	2020-01-01	2024-12-31

Annex 7. Biomass gasification projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
BIOMASS-CCU	823745	Biomass gasification with negative carbon emission through innovative CO2 capture and utilisation and integration with energy storage	1,168,400	846,400	2019-01-01	2022-12-31
BLAZE	815284	Biomass Low cost Advanced Zero Emission small-to-medium scale integrated gasifier-fuel cell combined heat and power plant	4,255,615	4,255,615	2019-03-01	2022-02-28
CLARA	817841	Chemical Looping gAsification foR sustainAble production of biofuels	4,993,805	4,993,805	2018-11-01	2022-10-31
COMSYN	727476	Compact Gasification and Synthesis process for Transport Fuels	5,096,660	5,096,660	2017-05-01	2021-04-30
CONVERGE	818135	CarbON Valorisation in Energy-efficient Green fuels	5,087,031	5,087,031	2018-11-01	2022-04-30
EFFIGAS	775720	Innovative self-controlling biomass gasification technology to improve the biogas efficiency achieving a top quality syngas	71,429	50,000	2017-05-01	2017-08-31
FLEDGED	727600	FLExible Dimethyl ether production from biomass Gasification with sorption-enhancED processes	5,569,330	5,306,455	2016-11-01	2020-10-31
FLEXCHX	763919	FLEXIBLE COMBINED PRODUCTION OF POWER, HEAT AND TRANSPORT FUELS FROM RENEWABLE ENERGY SOURCES	4,489,545	4,489,545	2018-03-01	2021-02-28
FlexiFuel-CHX	654446	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
FlexiFuel-SOFC	641229	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	2019-06-30
GAREP	673311	Novel GAsification REactor for combined heat and power Plant	71,429	50,000	2015-06-01	2015-11-30
HiEff-BioPower	727330	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	2021-09-30
Plasmapower	735818	PlasmaPower: hydro-catalytic plasma gasification for high-efficiency energy generation	71,429	50,000	2016-09-01	2016-12-31
RENEGAS	699122	RENewable AdvancEd GAsification FeedstockS	71,429	50,000	2015-08-01	2015-12-31
TES	673566	Total Energy System: innovative in-farm cogeneration plant for manure valorisation viable even for small farms	71,429	50,000	2015-05-01	2015-10-31
WASTE2GRIDS	826161	Converting WASTE to offer flexible GRID balancing Services with highly-integrated, efficient solid-oxide plants	528,750	528,750	2019-01-01	2020-06-30

Annex 8. Biomass algae projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
ABACUS	745668	Algae for a biomass applied to the production of added value compounds	5,135,861	4,653,659	2017-05-01	2020-04-30
Accordion Bioreactor	744603	An innovative high capacity Accordion bioreactor technology for high performance and low cost microalgae production	71,429	50,000	2017-01-01	2017-04-30
ALGAE4A-B	691102	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
ALGAMATER	767333	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		
algaPLUS	672596	Upscale and optimisation of an olive wastewater treatment photobioreactor (PBR) coupled to algae biomass valorisation as biofertilizer and treated water reuse	71,429	50,000	2015-05-01	2015-09-30
AlgCoustics	845185	Single-step disentanglement and fractionation of microalgal high-value products through acoustophoresis	187,572	187,572	2020-01-06	2022-01-05
AORTA	761743	Alginor`s Ocean Refining Total utilizing technology	71,429	50,000	2017-01-01	2017-06-30
AORTA 2	830698	Alginor's Ocean Refining Total utilisation Application	2,770,375	1,939,263	2018-09-01	2020-02-29
AQUACOMBINE	862834	Integrated on-farm Aquaponics systems for co-production of fish, halophyte vegetables, bioactive compounds, and bioenergy	11,072,052	9,789,884	2019-10-01	2023-09-30
BEAL	682580	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
BioMIC-FUEL	702911	Bio-inspired photonics for enhanced microalgal photosynthesis in biofuels	251,858	251,858	2017-01-01	2019-12-31
BIORECYGAS	711340	Farming high value algae with industrial gas emissions	71,429	50,000	2015-12-01	2016-05-31
BIOSEA	745622	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
Brevel	815821	A solar based, internally-illuminated bioreactor for microalgae cultivation	71,429	50,000	2018-04-01	2018-09-30
CMHAlgae	751637	Multifunctional Cellulose Magnetic Hybrid (CMH) Nanomaterial for Integrating Downstream Processing of Microalgae	160,800	160,800	2017-08-02	2019-08-01
ECO-LOGIC GREEN FARM	683515	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
INDALG	733718	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	INTERnational COmmercialization of innovative products based on MicroalgaE	2,426,438	1,698,506	2016-12-01	2018-11-30
IPHYC-H2020	673651	EU market research for an innovative algae based tertiary wastewater treatment system	71,429	50,000	2015-05-01	2015-10-31
MacroFuels	654010	Developing the next generation Macro-Algae based biofuels for			2016-01-01	2019-12-31

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
		transportation via advanced bio-refinery processes	5,999,893	5,999,893		
MAGNIFICENT	745754	Microalgae As a Green source for Nutritional Ingredients for Food/Feed and Ingredients for Cosmetics by cost-Effective New Technologies	5,886,265	5,330,259	2017-06-01	2021-05-31
MMM-REBIO	844909	Mixotrophy in marine microalgae for renewable biomass production	191,852	191,852	2019-11-04	2021-11-03
MONSTAA	749910	Metabolism of Novel Strains of Arctic Algae	231,642	231,642	42979	43951
SALTGAE	689785	Demonstration project to prove the techno-economic feasibility of using algae to treat saline wastewater from the food industry.	9,844,741	8,294,319	2016-06-01	2019-09-30
SE2B	675006	Solar Energy to Biomass - Optimisation of light energy conversion in plants and microalgae	3,866,945	3,866,945	2016-03-01	2020-02-29
VALUEMAG	745695	Valuable Products from Algae Using New Magnetic Cultivation and Extraction Techniques	4,789,000	4,789,000	2017-04-01	2020-03-31

Annex 9. Biomass biorefineries projects

Acronym	Project number	Project name	Overall Budget	EU Funding	Start	End
4REFINERY	727531	Scenarios for integration of bio-liquids in existing REFINERY processes	5,965,474	5,965,474	2017-05-01	2021-04-30
BIOFOREVER	720710	BIO-based products from FORestry via Economically Viable European Routes	15,237,406	9,937,997	2016-09-01	2019-12-31
BioMates	727463	Reliable Bio-based Refinery Intermediates	5,923,316	5,923,316	2016-10-01	2021-11-30
BIOrescue	720708	Enhanced bioconversion of agricultural residues through cascading use	3,767,588	2,635,141	2016-09-01	2019-08-31
BIOSKOH	709557	BIOSKOH's Innovation Stepping Stones for a novel European Second Generation BioEconomy	30,122,314	21,568,194	2016-06-01	2022-05-31
DEEP PURPLE	837998	CONVERSION OF DILUTED MIXED URBAN BIO-WASTES INTO SUSTAINABLE MATERIALS AND PRODUCTS IN FLEXIBLE PURPLE PHOTOBIOREFINERIES	9,527,581	6,983,050	2019-05-01	2023-04-30
ENGICOIN	760994	Engineered microbial factories for CO2 exploitation in an integrated waste treatment platform	6,986,910	6,986,910	2018-01-01	2021-12-31
FIRST2RUN	669029	Flagship demonstration of an integrated biorefinery for dry crops sustainable exploitation towards biobased materials production	25,022,689	16,995,882	2015-07-01	2019-06-30
GENIALG	727892	GENetic diversity exploitation for Innovative macro-ALGal biorefinery	12,224,238	10,885,817	2017-01-01	2020-12-31
IProPBio	778168	Integrated Process and Product Design for Sustainable Biorefineries	684,000	594,000	2018-01-01	2021-12-31
MACRO CASCADE	720755	MACRO CASCADE – Cascading Marine Macroalgal Biorefinery	4,316,426	4,156,356	2016-10-01	2020-09-30
SABANA	727874	Sustainable Algae Biorefinery for Agriculture aNd Aquaculture	10,646,705	8,848,524	2016-12-01	2021-05-31
TASAB	706642	TOWARDS A SUSTAINABLE ALGAL BIOREFINERY	183,455	183,455	2017-01-13	2019-01-12

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