# EERA-EIBI WORKSHOP REPORT

## *"LONGER TERM R&D NEEDS AND PRIORITIES ON BIOENERGY"*

# Bioenergy beyond 2020

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# Bioenergy beyond 2020

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## *"LONGER TERM R&D NEEDS AND PRIORITIES ON BIOENERGY"*

# Bioenergy beyond 2020

## 1. Motivation

To prepare for the likely post-2020 scenario, it is necessary to accelerate the development of advanced bioenergy technologies that already exist at pilot or small demonstration scale, but are unlikely to yield impacts before 2020. Beyond 2020 additional measures are needed and it is necessary to develop a fully new wave of biofuel technologies, which today are at a very early stage of development but offer considerable potential, or significant advantages with respect to current technologies, in the medium and particularly, in the longer term. Hence the importance of further promotion of this kind of research and development (R&D) within existing or future research programmes at national and EU levels.

With this this in mind the European Commission, through the Directorate General (DG) Research & Innovation, hosted the workshop "Longer Term R&D needs and Priorities on Bioenergy" in Brussels on 7$^{th}$ and 8$^{th}$ May 2013 and invited the European Energy Research Alliance (EERA) to organise a scientific workshop in close co-operation with the European Industrial Bioenergy Initiative (EIBI).

## 2. Background

The Bioenergy Roadmap and the EIBI Implementation Plan are focused on relatively mature and industrially relevant value chains that should be commercially available in the next five to ten years, and thus have the potential to contribute to the 2020 targets of the Renewable Energy Sources (RES) Directive. However, the EIBI also takes account of the post-2020 scenario for the low-carbon 2050 road maps and recognises the need to go beyond such targets, acknowledging that new technologies and value chains will be needed. Hence, a specific complementary activity on "Longer term R&D" was also included in the EIBI Implementation Plan.

Such medium and longer term R&D is mainly undertaken by public Member States (MS) and European Commission (EC) research programmes. Within the context of the Strategic Energy Technology Plan (SET-Plan), the medium and long-term R&D is mainly addressed by EERA. However, the EIBI considers that it would be beneficial to integrate an industrial perspective from a very early stage, in order to maximise the chances of future commercial success for such developments and to get maximum support from Research and Training Organisations (RTOs) to industrial development activities. This industrial perspective would constitute a valuable input for such programmes.

Within this background EERA Bioenergy organised a two-day workshop by inviting about 30 European experts, essentially engineers and scientists from industry and academia with different expertise and complementary backgrounds, to identify the longer term R&D needs and priorities on Bioenergy for Europe and with the aim of providing a technology vision and strategy for policy makers, programme owners and programme managers, including the European Commission and EERA Bioenergy. The strategy also integrated both the technical and the industrial/commercial perspectives. The future options for biorefineries and bioeconomy were also discussed and actions identified.

The workshop was focused on two specific goals:
i) Identifying the R&D needs of bioenergy technologies that currently exist at laboratory or pilot/demo scale, and which are capable of producing significant impacts in the medium-term (i.e., approximately between 2020 and 2025.
ii) Identifying bioenergy technologies with the potential to produce major breakthroughs in the long term (i.e., beyond 2025), as well as the main R&D challenges and needs for their development.

It was beyond the scope of the workshop to address issues such as marginal improvements of current bioenergy value chains in the market (e.g., first-generation biofuels, biogas/biomethane, combustion technologies for heat and power) or biomass availability and supply, although the latter is of paramount importance for addressing any bioenergy technology. The challenges for biomass supply and sustainability were mostly discussed within the context of the addressed technologies.

In this report a summary of the findings from the workshop is presented in terms of evolutionary and disruptive technologies. For each section, relevant R&D needs and priorities for power, and heat and transport sectors are separately addressed.

# 3. Introduction

## 3.1 Thermochemical biomass conversion

Thermochemical biomass conversion technologies are already utilised in four bioenergy value chains presented in the EIBI implementation plan:

a) synthetic liquid fuels and/or hydrocarbons (e.g., gasoline, naphtha, kerosene or diesel fuel) and blending components through gasification,
b) biomethane and other biosynthetic gaseous fuels through gasification,
c) high-efficiency heat and power generation through thermochemical conversion, of at least 45% to electricity,
d) intermediate bioenergy carriers through techniques such as pyrolysis and torrefaction.

In all these value chains there are also short-term industrial development activities on-going or in the planning phase, however no fully commercial scale units are in operation (NER300 projects).

Thermochemical conversion routes are especially suitable for a wide variety of types of lignocellulosic biomass, including residues from forest industries and agriculture as well as dedicated energy crops and short-rotation wood. In addition, many waste materials and residues from, e.g., biochemical-based biorefinery processing can be processed effectively by using thermochemical conversion technologies.

Different combustion methods are available in different size ranges from farm-scale heating to large-scale utility boilers with optimised steam cycles. There are many short- to medium-term R&D needs for issues such as fuel flexibility in stand-alone biomass boilers and in co-firing applications as well as in emission control of small-scale biomass stoves and boilers. For proper heat utilisation, biomass combustion systems provide overall conversion efficiencies of up to 90% to heat and power. Moreover, biomass combustion and co-firing acts as a stepping stone for other applications, such as the development of logistical systems and sustainability criteria and certification schemes, and through residue valorisation in biorefinery. Since many of these combustion and co-firing systems will continue to operate for several decades, it is important to apply them in the most efficient and effective way. However, direct combustion methods do not have significant potential to make a major breakthrough by dramatically increasing power production efficiencies from the present state of the art or to enlarge the end-user applications for biomass. Thus, long-term R&D efforts should be focused mainly on other thermochemical conversion routes, which have potential for:
a) Facilitating use of “difficult” biomass feedstocks for energy and chemical applications.
b) Increasing feedstock flexibility.
c) Opening new possibilities for using biomass in applications that are not feasible by direct combustion systems.

In this respect, dry/wet torrefaction, the various types of pyrolysis, and gasification are technologies with great potential. These technologies are presently entering the market slowly as attractive local incentives are put in place for investors into industrial markets. The first demonstration and flagship projects play a key role in increasing the use of biomass in the transport sector and other applications where traditional combustion technologies are not attractive. However, these technologies are still less mature than combustion and further R&D work offers huge possibilities to increase the use of biomass, which can also be used in the power and heat sector. Integrated cooling and RES hybrid applications in combined heat and power (CHP) production will create new markets for thermochemical biomass conversion, and also support next-generation solar fuels. The fast-growing solar- and wind-energy market will create new peak and back-up power opportunities. The substitute natural gas (SNG) market is promising for many bioenergy technologies and offers good energy-storage flexibility and accessible distribution systems in many countries.

## 3.2 Biochemical biomass conversion

Biochemical biomass conversion technologies are already in use in the remaining three bioenergy value chains presented in the EIBI implementation plan:
a) Ethanol and higher alcohols from sugar-containing biomass and lignocellulosic biomass.
b) Renewable hydrocarbons from sugar-containing biomass via biological processes and/or chemical processes.
c) Bioenergy carriers from $CO_2$ and light through micro-organism-based production, which can be upgraded into transport fuels and other valuable products.

These three value chains have very different technological maturities.

In Europe, short-term industrial demo plants are only present for producing cellulosic bioethanol as biofuel. At Kalundborg, Denmark, Inbicon A/S operates an advanced second-generation bioethanol demo plant that uses wheat straw. The first of its kind, an industrial bioethanol plant, is expected for Italy (Chemtex/Beta Renewables at Crescentino) this year that will use wheat straw and giant reed *Arundo donax* as feedstock. Abengoa (Salamanca, Spain) has already announced the conversion of its wheat straw to ethanol demo plant into a full commercial plant for municipal solid wastes (organic cellulosic fraction) to ethanol.

Butanol has also been identified and tested as an oxygenated fuel for blending into gasoline, and it has advantages over ethanol in this respect. The energy content of butanol is higher than that of ethanol and closer to that of gasoline and, more importantly, it has no compatibility, miscibility or materials problems. However, the cost of producing synthetic butanol from fossil fuels is extremely sensitive to the price of crude oil and for bio-butanol there are substantial R&D needs regarding micro-organism strain selection and development and bioprocess design, with an emphasis on continuous operation and recovery technologies.

Novel advanced biofuels, including higher alcohols and hydrocarbons, still require great technological developments when compared to lignocellulosic ethanol, namely with respect to yields and productivities. Moreover, these advanced biofuels are, in general, much more toxic to microbial cell factories than ethanol, and therefore the development of cost-effective technologies for continuous removal of advanced biofuels (or their precursors) from the fermentation broth is mandatory.

R&D priorities should be given to biomass-based sugar-to-hydrocarbon technologies focused on drop-in biofuels, in particular jet biofuels, since current commercial biofuels (bioethanol and biodiesel) do not meet the strict specifications of fuel for aircraft turbine engines. While bioethanol (a C2 molecule) and biodiesel (C16+ molecules) are used as drop-in fuels in spark-ignition and compression engines, respectively, jet biofuels need to accommodate C8 to C14 hydrocarbons in order to fulfil physical and chemical requirements like low freezing point (<-40°C) and, at the same time, to provide the necessary heat of combustion (>42 MJ/kg).

Current certified technologies for the production of drop-in jet biofuels include thermochemical conversion of biomass by gasification followed by Fischer-Tropsch synthesis and by hydroprocessing of esters and fatty acids (HEFA) from, e.g., vegetable oils. Technologies for the conversion of sugar-containing biomass into renewable hydrocarbons by biological and/or chemical processes are still at an early stage of development. Biological conversion pathways for condensation reactions that lead to hydrocarbons include fatty acid, polyketide and isoprenoid biosynthesis. Other technologies for the production of jet biofuels from sugars include chemical condensation processes like aqueous-phase processing of the dehydration and condensation of alcohols produced by fermentation. Alcohol-to-jet biofuel is now under the certification process and lignocellulosic ethanol can play an important (intermediary) role for jet-biofuel production.

## 3.3 European and global bioenergy market assessments beyond 2020 and the low carbon 2050 roadmap scenarios

The EC published their low-carbon roadmap for 2050 in 2011 which calls for deep decarbonisation of stationary energy and transportation fuels. Several European, regional and national energy systems have been reporting significant growth on the share of renewable energy sources. Concern over biomass sustainability for future energy, food and various product markets has been expressed, however very few European system studies and scenarios have been analysed. Top-down biomass-market-driven system studies are needed which integrate low-carbon and bioeconomy-based new technologies with commercial requirements for stepwise market introduction from 2020, 2030, 2040, and 2050. The complementary assessment of biomass availability, mapping, production strategies and markets will give relevant business feedback with recommendations for constructive incentives for new bioenergy technology development and demonstrations for all stakeholders within the EIBI and SET Plans.

# 4. Evolutionary thermochemical-based technologies

## 4.1 Power and heat sector

### *4.1.1 Biomass upgrading for bioenergy carriers*

Biomass has some special handling and processing features that require resolution for successful deployment. In particular biomass logistics is complex and costly, and the unusual properties of biomass present challenges in process design end-use which can affect costs.

Therefore, there is great interest in optimising biomass logistics and end-use by converting biomass into high-quality bioenergy carriers or intermediates close to its source. These carriers allow the decoupling of biomass availability and use in time, place and scale. Moreover, they enable application of advanced trading schemes similar to those for fossil fuels. Thermal upgrading technologies generally aim to fit into existing energy infrastructures, viz.:

- Torrefaction and hydrothermal carbonisation (wet torrefaction), and similar technologies to produce solid bioenergy carriers analogous to coal.
- Pyrolysis to produce liquid bioenergy carriers analogous to oil.
- Gasification-based production of syngas for further upgrading to gaseous fuels like biomethane which is fully compatible with the natural gas infrastructure or as compressed natural gas (CNG) and liquefied natural gas (LNG) for filling road-side filling stations in a process that minimises waste streams.

The first two will be discussed in more detail below, while the status and future R&D needs for the latter will be addressed in the section on gasification for transport-fuel production.

**Torrefaction and hydrothermal carbonisation (wet torrefaction)**

*i) Background and main advantages*

Torrefaction, hydrothermal carbonisation and similar thermochemical upgrading technologies that produce high-quality solid bioenergy carriers have attracted much attention in recent years. The products offer substantial logistical advantages compared to simple biomass and also compared to conventional pellets, e.g., they have high energy density (on a volume basis 3 to 5x higher than the original biomass, up to 50% higher than conventional pellets), good water resistance and very low biodegradation which allows outdoor storage. In addition, their excellent grindability and higher intrinsic energy density are advantageous in several major thermochemical end-use options such as pulverised-fuel combustion and entrained-flow gasification, where small, high-energy-density particles are required. Moreover, a more consistent product quality allows application of advanced transport and trading schemes similar to coal, which may further reduce the cost of logistics. Since these methods are basically applicable to all lignocellulosic biomass, these upgrading technologies have the potential to make a significant contribution to an enlarged raw material portfolio by including both agricultural and forestry residues. There is also potential to upgrade mixed residue streams of biogenic and fossil origin, such as paper-plastic fractions.

High-quality solid bioenergy carriers can be produced at an energy efficiency in excess of 90% in Lower Heating Value (LHV) terms, which leads to higher overall energy efficiencies of entire biomass supply chains, and simultaneously reduces the overall $CO_2$ footprint and cost compared to conventional pellets. Torrefaction is mainly used to upgrade relatively dry biomass (<50% moisture), while hydrothermal carbonisation (or wet torrefaction) and other hydrothermal processes process wet streams (typically

>50% moisture). Currently, several pilot and demonstration units have been realised in Europe, which mainly operate on woody biomass, and it may be expected that the first commercial units on woody biomass will start operating within 2–3 years when the market incentives, e.g., feed-in tariff for green electricity, are in place for investors. In the short-to-medium term, these solid energy carriers may give a major boost to the introduction of high-percentage co-firing of up to 100% repowering in coal-fired power plants. In the longer run, these upgrading technologies are considered to be important enablers for entrained-flow gasification-based production of biofuels and biochemicals.

*ii) Main barriers*

Although several of these upgrading technologies to produce solid bioenergy carriers are on the verge of market introduction, there are still significant technical barriers or challenges that have a negative impact on cost (e.g., through limited reliability/availability of production plants) and which limit the range of applications. The main barriers are as follows:

- Challenges in combining torrefaction with proper densification techniques. For many biomass feedstocks, densification of torrefied material is less straightforward than anticipated initially. Moreover, densification often involves a trial-and-error approach as the fundamentals are not yet well understood.
- There is still a lack of confidence among end-users as to whether these technologies can meet their expectations and whether safety issues can be managed properly. Production of larger product batches for more extensive end-use testing and product standardisation are required.
- Torrefaction of nonwoody biomass often requires additional processing or measures to meet end-user specifications, e.g., alkali and chlorine levels; these measures are still in an early stage of development.
- Hydrothermal carbonisation or wet torrefaction generally is at an earlier stage of development than dry torrefaction. Piloting, scale-up, industrial demonstration, optimisation of overall process concepts including effluent processing and economic assessment are still required to allow market introduction.
- There are different options for further process optimisation, e.g., heat integration/utilisation depending on biomass moisture content and production of high-value co-products, which are still underexplored.

*iii) Research priorities*

Currently, several promising technologies for the upgrading of thermochemical biomass into solid bioenergy carriers are in a pilot or industrial-demonstration stage. These pilot/demonstration efforts are supported by dedicated, mostly short-term, R&D efforts with a focus on woody biomass. In addition, several longer term R&D issues are now being addressed in two large EU-FP7 projects, namely, SECTOR and BIOBOOST. Given the existing barriers and the scope of these existing initiatives, it will be important to continue both demonstration/flagship efforts and supporting R&D in the 2014–2020 timeframe. Research priorities are:

- Demonstration/flagship projects to enable **production of sufficiently large quantities of consistent solid bioenergy carriers** for realistic industrial-scale combustion/gasification trials to build sufficient end-user confidence.
- Development of **optimised integrated torrefaction-densification concepts for woody biomass** feedstock and improvement of the fundamental understanding of densification technologies.
- Development of **torrefaction-based concepts for upgrading nonwoody biomass** feedstock that requires additional processing to meet end-user requirements.

- Piloting, scale-up, industrial demonstration and optimisation of **overall hydrothermal or wet torrefaction processes** including effluent processing.
- Development of process concepts with **optimised heat integration/utilisation** and/or production of high-value co-products for cost reduction.
- Introduction of **norms and standards** to improve trading prospects for solid bioenergy carriers.

### *iv) Timeline*

Demonstration/flagship activities in 2014–20:

- Industrial-scale combustion/gasification trials validating product quality of solid bioenergy carriers aimed mainly at increasing end-user confidence.

Medium- to long-term R&D topics in 2014–22:

- Optimised integrated torrefaction-densification concepts for woody biomass.
- Torrefaction-based upgrading concepts for nonwoody biomass feedstock that requires additional processing to meet end-user requirements.
- Piloting, scale-up, industrial demonstration and optimisation of overall hydrothermal or wet torrefaction process concepts.

Long-term R&D topics in 2020–24:

- Process concepts with optimised heat integration/utilisation and/or production of high-value co-products for cost reduction.

## Pyrolysis for energy carriers

### *i) Background and main advantages*

Fast pyrolysis is part of a family of processes that includes intermediate pyrolysis and slow pyrolysis for charcoal. Fast pyrolysis is a pretreatment process that yields a clean liquid as an intermediate product or energy carrier which is suitable for a wide variety of applications. During the last ten years, fast pyrolysis (FP) and its variants have become industrially interesting alternative to torrefaction for biomass preparation. Three FP-based processing alternatives may be distinguished: basic fast pyrolysis, catalytic pyrolysis, and hydropyrolysis. Each of these has some remaining technical challenges. Fast pyrolysis is only now entering the demonstration stage, and there is still room for entirely new FP concepts.

This technology makes it possible to produce biomass-derived oil on a large scale and to use this product in existing boilers and kilns that presently use heavy fuel. In the longer term, after further development, pyrolysis oil may also be utilised in other applications, such as high-efficiency internal combustion (IC)-engines or small-scale burners, to replace light fuel oil or natural gas. The use of pyrolysis oil in small- to medium-scale units will help to make efficient use of biomass resources in many applications where direct combustion of solid biomass is not attractive. One of the advantages of fast pyrolysis oil is that it can be transported and stored to be utilised as a back-up or fuel for peak power applications also in RES Hybrids. The main target of long-term pyrolysis R&D is high-quality and cost-effective transportation fuel as discussed in Section 3.2, but simple heating oil applications will pave the way towards industrial-scale pyrolysis technologies. There is an on-going establishment of standards with ASTM and CEN and this procedure must be maintained to allow free market trading of FP liquids.

### *ii) Main barriers*

Today, application of pyrolysis oil is used for heating and/or power by standalone combustion or co-firing. It is of the utmost importance that these applications are successfully demonstrated in the coming years to provide long-term experience. The main barriers of using biomass pyrolysis technologies for power and heat applications are the following.

- The quality of FP oil produced by the present processes limits the use of pyrolysis oil for many potential applications.
- The use of pyrolysis oil in IC engines or turbines is an interesting alternative which has, however, been hindered by lack of sufficient and/or consistent pyrolysis oil, and hence long-term operation experience is lacking.
- Limited feedstock (wood) and the need for high-cost feedstock pretreatment in the present FP technologies. With many high-ash feedstocks, the ash components reduce the oil yield and quality as more gas is generated.
- Challenges in minimising ash-related problems with agro-biomass and need for creating total ash-recycling systems with a closed loop of fertilisation of biomass crops (joint need for pyrolysis and gasification).

### *iii) Research priorities*

As described above FP processes and simple combustion applications should be demonstrated on an industrial scale in the short term to provide longer term experience. These first demonstrations and the supporting short-term R&D are of utmost importance for creating industrial experience on FP processes in the next years as well as in the use of the liquid. The longer term R&D priorities of biomass pyrolysis in power and heat applications are as follows:

- **Removal of solids from bio-oil** has been proven to be challenging. Hot vapour filtration has been proposed for near complete removal of solids from bio-oil, but R&D is still needed to improve and scale-up the technology to make piloting possible. Hot vapour filtration or similar solutions for pyrolysis vapours is critically important for situations in which no solids are allowed in products or intermediates.
- **Improvements of oil quality** by other relatively simple and cost-effective methods and other required developments so that pyrolysis oil can be used in IC-engines, to replace light fuel oil in small-scale heating and as back-up and peak fuel in RESHybrids.
- **New integrated concepts for pyrolysis oil production** targeting high-quality oil and high overall efficiency of biomass utilisation for fuel-oil replacements, power and heat production as well as for producing transportation fuels and valuable chemical products.
- **Continued development and introduction of norms and standards** for bio-oil is necessary for successful market introduction.

### *iv) Timeline*

Demonstration activities in 2014–20:

- Production of pyrolysis oil from wood for heating purposes by different alternative technologies.

Medium- to long-term R&D topics in 2014–22:

- Hot vapour filtration of pyrolysis oil.
- R&D into oil-quality improvements and using pyrolysis oils in IC-engines and other distributed power production systems.
- Development of norms and standards.

Long-term R&D topics in 2020–24:

- Novel concepts for integrated production of high-quality pyrolysis oil, heat and power as well as transportation fuels and high valuable primary products from biomass.
- Demonstration of the more promising biofuel and chemicals processes via fast pyrolysis.

### *4.1.2 Biomass combustion*

**i) Background and main advantages**

Different types of combustion methods are available for different size ranges. In the workshop, particular focus has been put on large coal-fired utility boilers and options and incentives for high-percentage-biomass co-firing and biomass repowering.

Coal-fired power plants are facing difficult times as they are large $CO_2$-emitters. High-percentage co-firing, even up to 100% biomass repowering, is an attractive option for many plants, which would ensure prolonged operation with a strongly reduced $CO_2$ footprint and thus avoid massive capital destruction. In the near term, this option allows several EU countries to meet their 2020 $CO_2$-reduction and RES targets in a cost-effective way. At the same time, it may constitute an attractive renewable energy option, which can pave the way for other options in view of:

- Boosting large-scale biomass transport, handling and utilisation and the associated development and implementation of stringent sustainability criteria and certification schemes.
- Providing flexible, regulatory power to support the further introduction of other renewable energy sources such as solar and wind.
- Being an important element in future biorefinery and cascading concepts. For example, heat can be used for other biomass processing, while the plant can be used to generate power and heat from biorefinery residues with high efficiency. These integration concepts may contribute substantially to the overall economics of biomass utilisation.

In all instances, clearly, proper heat utilisation is a prerequisite to ensure high overall biomass-to-energy conversion efficiencies. With proper incentives in place, full-scale implementation of CCS can be initiated, which in combination with high biomass co-firing levels may even lead to the creation of net carbon sinks. In summary, coal-fired power plants could be converted into multifuel combined heat and power (CHP) plants as cornerstones to the transition into a low-carbon economy.

**ii) Main barriers**

Many coal-fired utilities have turned to biomass co-firing already. But co-firing percentages have mostly been limited to below 25% (on an output basis), in some cases with true hybrid operation or full repowering on biomass, but the latter in older and/or smaller dedicated units only. For new (ultra-) supercritical units, generally no guarantees for biomass co-firing are given by the supplier, which hampers the introduction of biomass co-firing in these new units. Moreover, expensive clean wood pellets are mostly used, which in the near future are likely to become too expensive for this application due to an increasing market pull for the production of higher added-value products (e.g., transportation fuels and chemicals). A shift towards use of lower quality biomass including agroresidues, residues from biorefinery processing and mixed industrial residue streams will be required but additional R&D is absolutely necessary to convert low-quality biomass into high pellet quality at a low processing cost.

Another option to reduce the carbon footprint, carbon capture and storage (CCS), has been assessed in several piloting/demonstration projects, but this has not yet led to full implementation, mainly due to the absence of sufficient regulatory or economic drivers and to remaining technical uncertainties mainly concerning $CO_2$ storage.

**iii) Research priorities**

In general, the transition of coal-fired power plants into multifuel CHP plants with high-percentage co-firing (up to 100%) requires industrial-scale demonstration and gradual implementation closely supported by well-focused short-term R&D activities (e.g., performance prediction, detailed sampling/monitoring and Computational Fluid Dynamics (CFD) modelling). Industrial-scale demonstration should involve trials with high-percentage direct co-firing in new boilers with higher steam conditions and different advanced indirect co-firing processes utilising challenging biomass residues and waste feedstocks (see also section 4.1.3 Biomass gasification).

The priorities for longer term R&D on biomass co-firing and repowering are as follows:

- **Fuel engineering and milling/feeding strategies**: When pushing the limits of biomass co-firing and using lower quality biomass, advanced fuel pretreatment, upgrading (e.g., dry/wet torrefaction, pyrolysis) and mixing are essential. Proper fuel recipes and milling/feeding strategies will have to be developed to avoid operational problems, control emissions and assure the quality and utilisation of residue streams.
- **Further development of (advanced) indirect co-firing concepts** involving, e.g., (low-temperature) gasification to achieve high co-firing levels with challenging biomass residues and waste feedstocks and allow sufficient operating flexibility.
- **Performance prediction**: Further development, validation, comparison and application of predictive tools. The predictive tools to be considered include accurate CFD models for multifuel operation, empirical models and (small-scale) experimental assessment techniques.
- **Diagnostics and monitoring**: Diagnostics and (online) monitoring capabilities need to be brought to a higher level. Improved monitoring will involve the development of new techniques and associated sensors to assess various aspects of plant operation, such as fuel quality, slagging/fouling and corrosion. Improved diagnostics may include the alignment of capabilities and facilities at various institutes for sampling and analysis throughout Europe and lead to the formation of (international) measurement teams.
- **Development of integrated biorefinery concepts** involving large-scale power (and heat) plants.

**iv) Timeline**

Demonstration/flagship activities in 2014–20:

- Trials with high-percentage direct co-firing in new pulverised-fuel boilers with higher steam conditions, including application of (solid) bioenergy carriers.
- Advanced indirect co-firing processes that utilise challenging biomass residues and waste feedstocks.

Medium- to long-term R&D topics in 2014–22:

- Biomass upgrading technologies.
- Indirect co-firing concepts involving gasification and gas cleaning prior to combustion.
- Predictive tools.
- Diagnostics and (online) monitoring capabilities.

Long-term R&D topics in 2020–24:

- Integrated biorefinery concepts involving large-scale power (and heat) plants.

### *4.1.3 Biomass gasification*

**i) Background and main advantages**

Different power- and heat-production systems based on gasification technologies have been developed in the last decades. Various small gasifiers coupled to IC-engines are commercially available for small-scale production of power and heat from high-quality wood chips. However, their feedstock specifications are presently very limiting and their overall efficiency is low. Pressurised gasification of forest residues followed by hot filtration was developed in the 1990s for gas-turbine applications, but this technology has not yet been realised at an industrial scale. Co-combustion of gasified low-quality biomass and wastes in large utility boilers has recently become a commercially available alternative to replace fossil fuels in the European power sector and the first 50–150 MW gasifiers have been recently put into operation.

In the longer term, gasification technologies offer the potential for high-efficiency power production by advanced Integrated Gasification Combined Cycle (IGCC), gas engine and fuel-cell cycles. In addition, new types of combinations of material recovery and energy production will be possible for various kinds of industrial and biogenic waste fractions. These technologies are at a relatively early stage of development and there is still room for major improvements to be achieved by innovative R&D work.

The general advantages of biomass gasification technologies in the power and heat sector are:

- The possibility to produce power from biomass on a small scale (<5 MWe), which is not economically possible with ordinary combustion and steam cycles. High total efficiency, however, requires that heat generated can also be utilised or that state of the art gas engines should be replaced with fuels cells or some other new innovation. Integration of biomass gasification with biogas or solar and wind power (RESHybrids) offers interesting alternatives for farm- and village-scale production of renewable energy, in both rural and agricultural areas of Europe.
- Gasification followed by hot-gas filtration can also be applied to generate clean gaseous fuels from many low-grade fuels such as different wastes and straw. The removal of gas contaminants prior to combustion makes it possible to minimise corrosion and deposition in boilers. Recovery of valuable metals from waste gasification and different nutrients for fertilising purposes are interesting new possibilities for gasification-based technologies. In direct co-firing the biomass/waste-derived ashes are mixed with coal ash, which makes it difficult to recover valuable components.
- Large-scale high-efficiency power production by means of innovative and optimised power cycles, such as IGCC (integrated gasification combined cycles) or combined cycles with gas engines have the potential for over 45% electric efficiency together with over 80% total efficiency in CHP applications. Innovative combined power and cooling cycles are also interesting alternatives.

**ii) Main barriers**

The commercialisation of gasification systems has been rather slow and many promising technologies, such as biomass IGCC, have not yet been demonstrated on an industrial scale. Often, the main barriers to take-up of new high-efficiency technologies have been economic. Especially the economics of the first demonstration and flagship plants are very challenging and these often require long-term incentives. The main barriers to biomass and waste gasification in heat and power markets are:

- Lack of industrial-scale demonstration of biomass IGCC technology, small number of suitable gas turbines and limited experience of high-pressure biomass gasification required in medium- to large-scale high-efficiency power cycles.
- Challenges in ash sintering and fouling in gasification of agro-biomass and wastes for co-firing, and for more advanced power cycles.
- Limited experience of hot-gas cleaning and high cost of the present gas-cleaning systems.
- Limited knowledge of and solutions for recovery of valuable metals and recycling of nutrients from gasification ash, which would be needed for future combined material recycling and power production plants for waste-derived fuels and dedicated energy crops.

- Limited feedstock flexibility of small-scale gasifiers, low efficiency of small gas engines and high investments costs in small-scale combined heat and power production; new innovative solutions are required for farm/village-scale power.

**iii) Research priorities**

Demonstration of the most promising gasification technologies and realisation of the first flagship plants for the heat and power markets plays a key role in enhancing the market penetration of thermochemical biomass conversion systems and also in catalysing innovative R&D. The demonstration and flagship projects should be supported by well-focused short-term R&D activities, which should preferably be integrated with the demonstration projects. Often, the flagship plants can also be utilised as R&D platforms, where slip-stream testing of new innovations can be effectively realised. These collaboration activities will be emphasised in the joint EC ERANET calls and EIBI activities. The following demonstration activities were prioritised in the presentations and discussions of this EIBI/EERA meeting:

a) Industrial-scale realisation of **simplified IGCC** based on pressurised gasification and hot-gas cleaning.

b) Demonstration and full-scale realisation of different **advanced co-firing processes** that utilise challenging biomass residues and waste feedstocks.

The priorities for longer term R&D on biomass gasification for heat and power markets are:

- Improvements to **pressurised biomass gasification** and to hot-gas cleaning for gas-turbine applications and for other high-efficiency power systems; integrated gasification and contaminant removal systems with reduced capital expenditure (Capex) and improved availability.
- Access to a **pressurised gasifier facility** for testing and development.
- New technologies for gasification of **biomass from agricultural crops** and energy crops and innovative concepts for using biomass-derived ash streams for fertilisation purposes.
- **Waste-gasification systems** with over 40% electrical efficiency, with heat recovery and integrated recovery of valuable metals from the ash streams.
- Innovative new solutions for **fuel-flexible small- to medium-scale (<5 MWe) combined power and heating/cooling applications**, possibly which integrate different conversion and power production methods; village-scale power and heating/cooling with over 80% overall biomass utilisation efficiency.

**iv) Timeline**

Demonstration/flagship activities in 2014–20:

- Pressurised gasification with hot-gas filtration connected to IGCC in CHP applications with wood fuels, in the size range of 20–60 MWe; realisation either as a standalone biomass power plant or integrated into existing power plants (up to three plants in EU programs).
- Co-firing of high-alkali biomass and/or different waste streams using biomass gasification followed by gas cleaning prior to combustion (up to three plants for different fuels or applications).

Medium- to long-term R&D topics in 2014–22:

- Improved hot-gas cleaning methods for large-scale biomass gasification that utilise integrated contaminant removal technologies for tars, particulates, trace metals and chlorine. Gas cleaning is the key unit operation in enlarging feedstock flexibility and the variety of end-use applications of biomass gasification.
- Innovative methods for utilising the ash streams of biomass and waste gasification.

Long-term R&D topics in 2020–24:

- Biomass-to-energy concepts with a closed loop of nutrients; use of woody or herbaceous biomass for high-efficiency energy production and recycling of nutrients for fertilisation purposes.
- New small-scale village power systems (<5 MWe) with over 80% biomass utilisation efficiency and at least 35% electrical efficiency, achieved by novel integration of conversion technologies and prime movers as well by novel overall system integration (heating/cooling, industrial use of part of the biomass).

## 4.2 Transport fuels

### *4.2.1 Gasification and synthesis technologies*

**i) Background and main advantages**

Advanced second-generation biofuels can be produced from a wide variety of biomass feedstocks by utilising many different thermochemical conversion pathways. Gasification technologies produce syngas which can be further processed to yield high-quality transportation fuels such as diesel fuel, methanol/dimethyl ether (DME), gasoline, SNG[1] or hydrogen. In spite of recent extensive R&D efforts, syngas technologies for transportation fuels or chemicals have not yet made a commercial breakthrough. Syngas processes are very complex and require a large scale in order to achieve positive economics, which, together with technical uncertainties and availability risks, has resulted in difficulties in financing the first of their kind industrial plants. Both oxygen-blown pressurised gasification systems and atmospheric-pressure dual-fluidised-bed gasifiers have recently been demonstrated in pre-commercial pilot-scale plants and there are plans to realise the first industrial reference plants by the end of the decade.

In spite of the recent industrial activities, the state-of-the-art gasification processes are still far from ideal and there are many possibilities for improving the overall biomass conversion efficiency as well as reducing the complexity of the process and the capital and operating costs. Generally, the three main advantages of using gasification-based biomass conversion in the transport sector are:

- All biomass types and other carbon-containing feedstocks (e.g., waste) can, in principle, be used as the feedstock for transport-fuel production.
- A wide variety of synthesis processes and gas processing methods are available from conversion of natural gas, coal and oil to allow production of different alternative fuels.
- Gasification and synthesis processes can be integrated with other biomass industries (e.g., pulp and paper, saw mills, sugar cane, etc.) to optimise the overall efficiency of biomass utilisation and conversion into valuable products and by-product energy.

Moreover, gasification-based biomass to liquid fuels (BTL)-concepts are also considered to provide most attractive options for BioCCS due to the availability of $CO_2$-rich side streams.

**ii) Main barriers**

Most of the developed BTL-concepts can be realised only on a large or very large scale because state-of-the-art gas-cleaning and synthesis processes have been developed for the chemical industries and for coal and natural conversion processes. These concepts are attractive in large BTL units such as those in

[1] *It should be noted that gasification-based substitute natural gas (SNG) in the form of compressed natural gas (CNG) can be applied as a transportation fuel, but it can also replace natural gas in natural gas grids. Both applications will be taken into account in this section. In this respect, BTL concepts incorporate SNG production.*

European ports and oil-refining areas (e.g., Rotterdam), where large-scale logistics are maintained by marine transport and international biomass trade. However, usually, the scale of economy is completely different for biomass collection, biomass gasification reactors and for the utilisation of the by-product heat. This contradictory scaling issue may be the largest challenge in application of the presently developed BTL technologies based on gasification and synthesis.

The main barriers in application of thermochemical biomass conversion processes for commercial production of second generation transportation fuels are:

- The very large scale of operation (>100–200 kton/a capacity) required to reduce specific investment costs in concepts based on pressurised-oxygen blown gasification, deep gas cleaning and classical synthesis processes. This often results in increased biomass costs and in difficulties to utilise the by-product heat.
- The challenges of large-scale first of a kind production units with high engineering and contingency costs, difficulties of managing any technical and availability risks, and challenges in organising the required long-term incentives for the plants. Smaller scale demonstrations are usually limited to part of the process and thus the risk levels are often too high when entering into large complete-production units.
- Lack of proven gasification-based BTL-solutions for smaller scale applications (capacity of 30-100 kton/a) with reduced process complexity and with improved integration to heat and power production.
- Technical challenges of increasing the operation pressure of $O_2$-blown gasifiers (to 20–30 bar) or in pressurising the indirectly heated dual-bed gasifiers; this would reduce electricity consumption and thus improve the overall efficiency. Limited solutions for integrated hot-gas cleaning technologies, which would reduce the process complexity and improve the syngas production efficiency from the presently suggested NER300 technologies.
- The incorporation of BioCCS in BTL-concepts will depend mainly on incentive levels for CCS and on development of the storage infrastructure.

**iii) Research priorities**

Although several gasification-based projects were approved in the first NER300 call, no investment decisions have so far been made and probably many of the proposed projects will not be realised. The second call in July 2013 might bring in new attractive flagship projects, which would be crucially important to the whole value chain of forest biomass to transportation fuels. In order to limit the technological risks, the first production units could be realised using some of the well-proven final conversion methods, such as methanol, SNG or hydrogen-to-oil refinery. The sites for first plants should be selected so that there are no risks in biomass logistics and the technical support would be easy to arrange. Flagship plants should preferably also be utilised for slip-stream testing of advanced gas cleaning and synthesis technologies.

The long-term R&D activities should be focused on concepts and technologies that have the potential for maximum overall biomass utilisation efficiency, which should be on the same level as is achieved in combined heat and power production (biomass utilisation efficiency >75% in energy units). Innovative new solutions to dramatically increase efficiency and reduce process complexity and capital costs should be targeted, with the following priorities:

- **Increased operation pressure** (from present 4–10 bar to 20–30 bar) and improved hot-gas-cleaning process in $O_2$-blown fluidised-bed gasification processes for medium- to large-scale applications (BTL or SNG production at the scale of 70–300 kton/a).

- Novel concepts for **integrated production of fuel, power and heat** (CFHP) based on low-pressure (1–5 bar) dual-bed gasifiers equipped with secondary reforming of hydrocarbons and/or simplified final gas cleaning ($H_2$, SNG and BTL production in 20–100 kton/a scale).
- New solutions for **high-efficiency gasification of liquid biomass feeds**, such as co-gasification of black liquor and other liquid waste streams or pyrolysis oils. The use of black-liquor sodium as gasification catalyst.

Moreover, further development and demonstration of carbon-capture technology should be initiated to pave the way for BioCCS. This development would allow rapid deployment of the technology when CCS infrastructure and services are commercialised.

**iv) Timeline**

The first industrial BTL plants could start operation probably before 2020, if positive investment decisions are made in 2014–15 (depending mainly on risk-sharing solutions for investors). Thus, these plants could already have made some contribution to the transportation fuel targets by 2020. However, at present it seems likely that significant market penetration will require new technologies, which can be realised with improved biomass utilisation efficiency, lower investment costs and at smaller plant size, so that integration with biomass supply and to heat-consuming industries can be better achieved. As the industrial demonstration and construction of first production units of new technologies will take at least 5–7 years, all the above R&D activities should be started immediately so that industrial demonstration could be organised by around 2020 and some of the results could also be utilised to improve the economics of the planned first flagship projects.

### *4.2.2 Pyrolysis routes*

**i) Background and main advantages**

Upgrading is required before fast pyrolysis oil can be used as a transportation fuel. Improvement of the product by direct application of a catalyst in the pyrolysis process is one method which requires further research. Catalytic pyrolysis may be used at atmospheric-pressure units as a first step towards the final upgrading or in high-pressure catalytic hydropyrolysis processes as another alternative. Another basic route is the catalytic hydrodexygenation (HDO) of flash pyrolysis oil carried out as a separate secondary step. In addition, there are interesting alternatives for using pyrolysis oils as the renewable feed in oil refineries or in other type of biorefineries and future bioeconomies. Pyrolysis oil can also be fed into high-pressure gasification systems much easier than heterogeneous low-bulk density solid biomass. Pathways for pyrolysis-based transportation fuels are not as well developed and tested as the syngas-based alternatives, and they seem to have, at least in principle, a good potential for reduced capital and operating costs. In addition, pyrolysis-based concepts make it possible to separate the initial biomass conversion step and the oil upgrading and/or final production drop-in fuels. There is still definitely plenty of room for new innovative technologies to utilise pyrolysis oil as an intermediate energy carrier.

**ii) Main barriers**

Fast pyrolysis liquid, often also called bio-oil, is a complex mixture of mainly oxygenated hydrocarbon fragments derived from the biomass structure. Typically, it contains around 25 wt% of water and its pH value is below 3. The heating value of the liquid is in the same range as solid biomass. Common organic compounds used for FP include acetic acid, methanol, aldehydes, ketones, furans, alkyl-phenols, anhydrosugars, oligomeric sugars and lignin-derived compounds. The upgrading of pyrolysis vapours or oil into a high-quality transportation fuel is a challenging task which has not yet been developed to industrial level. The other main barrier of pyrolysis technology is the lack of industrial experience, even from simple heating-oil applications; all present demonstrations are focused on using wood as the feedstock, while there is important potential also for using other biomasses, such as agricultural residues and energy crops.

**iii) Research priorities**

Fast pyrolysis and its variants have been studied in laboratories already since the 1980s, but they have only recently become an industrially interesting possibility. Three FP-processing alternatives may be distinguished: base pyrolysis, catalytic pyrolysis, and hydropyrolysis. Each of these has certain interesting possibilities for process improvements. In addition, there is still also room for entirely new FP concepts. The following topics are high-priority R&D tasks of pyrolysis technology in the transport sector:

- **Catalytic pyrolysis** may be used for improving the quality of raw pyrolysis oil, but often improved quality is achieved at the cost of reduced oil yield. Especially more catalyst development work is required to bring this emerging technology to the pilot stage. Existing typical catalysts developed for mineral-oil applications have been tested, but only limited specific development work has been reported.
- **Pressurised hydropyrolysis** (HP) and its potential variants may prove interesting alternatives. Bio-oil from HP has been reported to be of high quality. However, reducing production cost for this concept would be important. Particularly, operation at lower pressures closer to 5 bar (instead of 10–20 bar) would be technically much more realistic. Development of more specific catalysts is also required to reach the potential of this technology.
- **Upgrading of primary bio-oils** is a critical step in biomass liquefaction. Several alternative technologies are available, however, only hydrodeoxygenation (HDO) may be ready for piloting. Several other upgrading routes are available, but more development is needed before these are ready for scale-up. Primary bio-oils from basic pyrolysis, catalytic pyrolysis, and HTL all produce oil that still needs to be upgraded for higher value fuels, including transportation fuels. **Integrated concepts, where bio-oil is used as a partial feed** in oil refinery or co-utilised with palm oil and other vegetable oils in presently developed hydrotreated vegetable oil (HVO) processes, are also important topics of R&D work. In addition to integration into the final conversion site, the primary oil production can be integrated into different power and heat systems to result in maximal overall chain efficiencies.

Some reports have also been made concerning the use of nonconventional technologies, such as microwave pyrolysis, although the scaling to larger volumes and considerable necessary improvements in energy efficiency and scoping of longer wavelength energy sources (e.g., radiofrequency heating) are still unsolved barriers.

**iv) Timeline**

The first industrial-scale pyrolysis units are just in the construction or planning stages and will be operational for heating-oil applications around 2015. All suggested pyrolysis-based technologies for transportation fuels are at a still-earlier stage and the R&D activities can be assumed to lead to first industrial demonstrations in 2020 or later. Thus, all R&D on pyrolysis-based transportation fuels can be considered to be long-term R&D.

# 5. Evolutionary biochemical-based technologies

## 5.1 Transport fuels

### *5.1.1 Biofuels via classical biomass fermentation pathways*

**i) Background and main advantages**

Among biofuel value chains, second-generation ethanol is at the forefront of the biochemical conversion of lignocellulosic biomass into ethanol. This value chain is now so mature that a couple of industrial units are fully operational in Europe, in the USA and in Brazil (e.g., Chemtex/Beta Renewables at Crescentino, Italy; Poet-DSM at Iowa, USA; Abengoa at Hugoton-Kansas, USA; GranBio, Alagoas, Brazil). The capacities announced are around 50–80 kt/a. Technology risk is no longer seen as the main barrier to investment. The main objective is now to lower the production cost to be competitive with gasoline to avoid long term reliance on regulation. Each step of the biochemical process still should be improved and the global integration of the whole value chain is of paramount importance to reduce risk and increase asset rotation.

**ii) Main technological barriers**

For lignocellulosic biofuels, in spite of significant technology improvements that have lowered the costs, e.g., enzyme costs decreased five times in the last ten years, there are still significant challenges concerning the production of sugar from many biomass feedstocks. Yields and productivities need further improvement and operational costs need to come further down to reduce the cost gap to petrochemical fuels. The competitive performance of a large-scale biochemical-based biofuels plant is also uncertain, since commercial-scale plants are lacking. In Europe, the recent Chemtex/Beta Renewables plant at Crescentino (Italy) will be very important to assess the economic feasibility for lignocellulosic ethanol.

The main technological barriers in applying biochemical biomass conversion processes for commercial production of second-generation transportation lignocellulosic biofuels are:

- Biomass (bio)chemical deconstruction into main fractions, and hydrolysis into simple sugars.
- Improvement of enzymes and micro-organism performance.
- Cost-effective drying of lignin for energy production or alternatives for lignin applications.
- Integrated energy optimisation to produce fuels, heat or power.
- Flexible feedstock biorefinery concept using a wide range of raw materials.

**iii) Research priorities**

Several different R&D areas need to be worked on, and the various biofuels of current interest (bioethanol, butanol, higher alcohols, biomethane, biohydrogen, etc.) are at very different stages of maturity. Complementary expertise from several fields (e.g., engineering, biochemistry, microbiology) must be applied together to advance the processes. Concerning biochemical-based lignocellulosic liquid biofuel technologies the following topics are high-priority R&D tasks:

- **Engineering plant-sugar potential**. Feedstock with changed properties through modern crop-breeding approaches and plant-cell-wall engineering to solve the dilemma of supporting biomass normal growth associated with a reduced amount of cell lignin without damaging cell transport tissues due to the functional role of lignin. This development could come about through novel plants with a modified composition, or with, e.g., self-induced enzymatic degradation.
- **Biomass deconstruction**. In spite of recent advances, the complete release of cellulose and hemicelluloses without production of microbial inhibitors is still a challenge. The pretreatments

used by the future industrial units are quite different but some common issues will be shared: integration with the enzymatic hydrolysis, energy-chemical consumption reduction and chemicals recycling or post-treatment. Greater understanding of the physical and chemical mechanisms taking place is required; either to be able to follow the different biomass-degrading products generated or to target the production of certain chemicals. A step further would allow use of a biochemical process as a part of the pretreatment, e.g., using synthetic biology through consolidated bioprocessing (CBP) approaches.

- **Enzyme improvement and integration of enzymatic hydrolysis**. Understanding of the deactivation mechanism of enzymes is still pending. Progress on that matter would probably lead to the same type of breakthrough made by the introduction of solid-supported catalysts in the past. Bioprospecting and engineering of novel enzymes for efficient enzymatic hydrolysis at high temperature, high specificity and minimal end-product inhibition are priority R&D topics. Additionally, enzyme recycling and other enzymatic-hydrolysis integration approaches (SSF, immobilisation, etc.) are mandatory to reduce enzyme and process costs.
- **Improving fermentative pathway performance**. Metabolic engineering and synthetic biology to provide novel cell factories both for the production of advanced biofuels and for larger scope of substrate utilisation (e.g., fermentation of both C6 and C5 molecules), while keeping or improving their robustness, is of the utmost importance. The development of such optimal cell factories will allow process intensification for the production of a wide range of end-products, e.g., lower and higher alcohols/alkanes. As far as SSF is concerned, thermostable micro-organisms are needed. Recycling of micro-organisms is of possible interest but its technical viability is dependent on process configuration.
- **Process intensification.** An overall issue in the biochemical processing is the need for process intensification. Process optimisation will require higher solid loadings in the pretreatment and hydrolysis and higher sugar concentrations in the fermentation to lower the cost of water/biofuel separation and decrease capital costs. R&D is required here on, e.g., enzyme adaptation to the liquefaction process and tolerance of micro-organisms to higher substrate, product and inhibitor concentrations.
- **Downstream processing**. Novel technologies, such as extraction by compressed fluid, pervaporation, membrane distillation, electrodialysis or liquid-air through membrane technologies, need to be further developed. There is potential to obtain energy and/or cost savings in comparison to classical technologies (distillation, solvent extraction).
- **Lignin upgrading**. Lignin is a non-polysaccharidic biomass component that constitutes between 10–30% of biomass. R&D is needed for the cost-effective drying of lignin for energy production. The lignin fraction has a great potential for production of a variety of chemicals. However, novel technology is needed to achieve this.
- **Biorefinery integration.** Further research and examples are needed into the integration of steps into existing processes such as integrated enzyme production and of diverse industrial operations to optimise the flow of raw materials, by-products and energy, integrated with local biomass-production systems.

**iv) Timeline**

Demonstration activities in 2014–20:

- Production of biofuels from lignocellulosic (cellulose and hemicellulose) biomass by different fermentative technologies and bioprocess configurations.
- Novel concepts for process intensification (pretreatments, enzymatic hydrolysis, fermentation and product recovery).
- Energy-efficient techniques for energy production from different types of lignins.

Medium- to long-term R&D topics in 2014–22:

- Bioprospection of lignocellulolytic enzymes with greater catalytic activity and stability under harsher process conditions.
- Engineering current fermentative micro-organisms for improving tolerance of inhibitors, total sugar utilisation and, simultaneously, high biofuel productivity.
- Low-energy demanding product recovery technologies.
- New terrestrial biomass crops (including breeding and cell-wall engineering programmes) for enhancement of biomass quality to ensure its suitability for bioenergy applications.

Long-term R&D topics in 2020–24:

- Novel (less energy-demanding and sustainable) pretreatments, including use of ionic liquids and ultrafine milling.
- Understanding enzymatic catalysis in heterogeneous media (solid-liquid slurry).
- Novel robust cell factories for efficient biofuel production through the use of both bioprospection technology and synthetic biology, towards consolidated bioprocessing.
- Energy-efficient techniques for upgrading lignins to high-added-value products.
- Better understanding of the biochemistry and molecular topology of the lignocellulosic wall and elucidation of the dynamics of the interaction amongst their components at different process stages.

### *5.1.2 Sugars to hydrocarbons*

**i) Background and main advantages**

The strict specifications of fuels for aircraft turbine engines are not met by current first-generation biofuels, which require fuels with properties like high energy and density and, at same time, low freezing point. The challenge is to obtain a C8-C14 range of renewable hydrocarbons to be used as drop-in jet biofuels. Technologies for the production of drop-in jet biofuels include thermochemical conversion of biomass through gasification followed by Fischer-Tropsch synthesis, and hydroprocessing of esters and fatty acids (HEFA) from vegetable oils. Alternatively, biochemical routes, through the use of biological and/or chemical conversion processes, can be tuned to generate specialised products (tailor-made biofuels) from renewable carbon sources. The biological routes from sugars for hydrocarbons still need to be optimised through the exploitation of carbon-carbon condensation biochemical pathways like fatty acid and isoprenoid biosynthesis. For some pathways, the chemical routes for the conversion of sugars or alcohols to hydrocarbons are interesting alternatives to biological conversions. Such alternatives include both aqueous-phase processing of sugars and dehydration and condensation of alcohols. Alcohol-to-jet biofuel is now under the jet-biofuel certification process, where lignocellulosic ethanol can play an important (intermediary) role.

**ii) Main technological barriers**

Apart from the main similar technological barriers encountered for lignocellulosic ethanol, e.g., advances in biomass deconstruction and improvements in C6- and C5-sugar assimilation by cell factories, sugar to hydrocarbon technologies still require R&D progress, namely with respect to yields and productivities. Moreover, these advanced biofuels are in general much more toxic to microbial cell factories than ethanol, and therefore the development of cost-effective technologies for continuous removal of advanced biofuels (or their precursors) from the fermentation broth are mandatory. The cost-effective upgrading of sugars or fermentation products to hydrocarbons is still a challenge in terms of energy-efficiency. Integrated biorefineries could be the key for the economic viability of these pathways.

**iii) Research priorities**

The research priorities for the deployment of renewable hydrocarbons from sugars include:

*For biological conversion:*

- **Development of novel and robust cell factories**. Synthetic biology and metabolic engineering will play an important role in the design of pathways towards the production of fermentation products like isoprenoids, fatty acids and polyketides at high yields and productivities. The increased tolerance to new fermentation products is also a clear priority in the development of industrial cell factories.
- **Development of cost-effective downstream processes**. The strong inhibitory effect of hydrocarbon molecules resulting from fermentation in their own biological conversion requires continuous removal of the fermentation product. This removal can be achieved by process intensification to couple the downstream processing to the biological conversion.

*For chemical conversion and upgrading of biological products:*

- **Hydrogenation of fermentation products**. The recovery of fermentation products will be followed, in several cases, by hydrogenation to obtain hydrocarbons as drop-in biofuels. Process integration, in hydrogen-producing biorefineries, is required to achieve cost-effective technologies that make use of biomass fermentation followed by hydrogenation. However R&D efforts are still necessary for efficient production of biohydrogen at reasonable costs (comparable to petrochemical industry prices).
- **Energy-efficient chemical conversions**. Aqueous-phase processing of sugars and dehydration and condensation of alcohols require energy-efficient processes. It is thus important to maximise the yield from the raw material and to run at high-solid contents to reach acceptable energy requirements. Moreover, lignin valorisation is a key R&D priority to improve the overall economics of biochemical-based biofuels production.

**iv) Timeline**

All sugar-to-hydrocarbons technologies for transportation fuels and chemicals are still at an earlier stage than those for biomass fermentation, and the successful R&D activities can be assumed to lead to first industrial demonstrations by 2020 or later. Thus, the whole R&D can be considered to be long-term R&D as follows:

Medium- to long-term R&D topics for 2014–22:

- Improve end-product tolerance through cell-factory development.
- Microbial bioprospection technology associated with high-throughput screening methods and advanced bioinformatics tools for identification of the most suitable microbial industrial platforms.
- Engineering higher yield metabolic pathways for biofuel synthesis.
- Process integration and developing in situ separation processes to minimise costs and energy requirement.
- Lignin valorisation through chemical conversions.

Long-term R&D topics for 2020–24:

- Advanced consolidated bioprocessing to be demonstrated at industrial scale by integrating robust cell factories displaying new biochemical/chemical routes.
- Novel concepts for efficient catalytic processes for the carbon-carbon condensation reactions using sugars and carbohydrate derivatives.

### *5.1.3 Biofuels from algae*

**i) Background and main advantages**

Micro- and macroalgae are complementary for the production of biofuels. Microalgae are primarily envisioned for the production of lipids while seaweeds can mainly be used to produce carbohydrates. Currently, there is no pilot-plant facility installed in Europe specifically for production of bioenergy carriers from $CO_2$ and light through micro-organism-based (microalgae) production and upgrading into transport fuels and valuable products. However, there are some microalgae plant facilities in The Netherlands (ALgaeParc, Wageningen) and in the south of Europe that might be reconverted to bioenergy purposes. Amongst them, the currently largest European microalgae closed-photo-bioreactor pilot facility belongs to AlgaFuel and is located in Pataias (Portugal). It constitutes an outdoor unit 1200 $m^2$ of photo-bioreactors containing about 1300 $m^3$ of algal culture, has been in operation since 2013 and aims to be a trial bed that targets sustainable production of biofuels in the longer term. The theoretical maximum oil productivity from algae is about 354,000 L $ha^{-1}$ $year^{-1}$ of unrefined oil which is several orders of magnitude higher than is possible with current agriculture-originating oil crops. Since realistic oil yields from microalgae will be well below the theoretical yield, R&D efforts are still needed for microalgae to demonstrate their potential to be an effective technology for advanced biofuels.

Macroalgae or seaweed also have great potential for energy applications (including transportation fuels). Seaweed contains up to 70% carbohydratesand there is the potential of converting them into transportation fuels and chemicals. Unlike lignocellulosic biomass, seaweed does not require land, special nutrients or sweet water, and since seaweed is a plant, farming and harvesting can be done in an energy-efficient way. Seaweed is the fastest growing, most efficient photosynthetic plant at European latitudes (yields of 20 ton/ha/y on dry basis can be reached) and grows best under rather cold conditions; the plant growth season is in winter. Sparse initiatives have been started to cultivate and biorefine seaweed to form liquid energy carriers.

**ii) Main technological barriers**

Current research on algae (micro- and macro-algae) is not only focussing on improving traditional food and feed supplement products but also on new algal products like biodiesel, bioethanol, higher alcohols, hydrogen, hydrocarbon-type molecules, and a wide range of chemicals. For bioenergy, the challenge for algal biofuel systems is to increase the efficiency of both the production of algae and the conversion of the biomass into a useful energy carrier that is energetically self-sufficient and sustainable in terms of global-warming potential. This aim is more difficult to attain for microalgae cultivated in closed systems (photo-bioreactors) than for raceways. Research efforts into bioenergy from microalgae should therefore be mostly focussed in the former type of cultivation. The current production costs of oil from microalgae are still one order of magnitude higher than those of biodiesel from vegetable oils. For macroalgae the main challenge is to adapt the sugar-based routes to the different types of carbohydrates found in seaweeds. Different seaweed species have totally different carbohydrate make-ups, with many sugars present in large quantities which are not normally found in lignocellulosic biomass. Further challenges include the cultivation of seaweed to secure a consistent raw material. Preliminary economic evaluations suggest that the production costs need to come down by factors, not orders of magnitude, to become economically viable.

**iii) Research priorities**

In the case of macroalgal biomass (seaweeds), there is a need for R&D either for bioprospecting of novel species or genetic improvement of the existing ones to broaden the availability of tractable micro-organisms that can metabolise alginate and other recalcitrant polysaccharides. Metabolisation of as much of the sugar in seaweed as possible is essential for the efficient production of biofuels. Another

R&D needs that is a long-standing bottleneck in microalgae is improvement of energetically efficient technologies for cell harvesting. New concepts should be developed, e.g., to produce ethanol directly asn a readily usable biofuel from $CO_2$ and light by means of engineered autotrophic strains that use inexpensive nutrient media such as wastewaters. This step requires a heterologous fermentation with an improved fermentation pathway of recombinant strains, elimination of competing pathways through gene knock-out and a sharp increase in the ethanol tolerance of those recombinant algae strains. The energy efficiency for the conversion of sunlight into ethanol can reach about 15%. Upgrading of co-products is essential. Any algal biorefinery should integrate several different integrated conversion technologies to produce biofuels including biodiesel, green diesel, green gasoline, aviation fuel, ethanol, methane and hydrogen, as well as valuable co-products, such as specialised fats, long-chain poly-unsaturated fatty acids, pigments, and other products.

The following topics are high-priority R&D tasks for algal technology in the transport sector:

- **Metabolic engineering**: To develop robust, specialised industrial algal strains. Special attention should be devoted to the development of mutants with shorter chlorophyll antenna size in the photosystems that exhibit higher intensity for the saturation of photosynthesis and greater light-saturated photosynthetic activity. Such work should yield improved solar energy-conversion efficiency and photosynthetic productivity under mass culture and bright sunlight, outdoor conditions.
- Cost-effective **biomass preconcentration, harvesting, disruption and extraction** methodologies at demonstration and commercial scale.
- Bioprospection and expression of **novel enzymatic pathways** for the hydrolysis of recalcitrant seaweed polysaccharides as well as the incorporation of the monomers into a productive biochemical cycle.
- Cost-effective **dewatering of seaweed**, as seaweed contains up to 85% water. Chlorine management should be addressed also.
- Biorefinery: To expand (micro- and macro)algal technology as a major cost-effective industrial process for the production of energy and chemicals.
- Production of **novel advanced biofuels (jet fuel, others) from seaweeds**. Novel hydrolysis (chemical and enzymatic), fermentation and carbohydrate conversion processes based on seaweed-specific carbohydrate molecules.

**iv) Timeline**

Demonstration/flagship activities in 2014–20:

- Direct liquid biofuels from micro-/macroalgae using a non-fresh water concept (up to three plants in EU programs) operating successfully; at Technology Readiness Level 7 (TRL 7).
- Smart cost-effective microalgal biomass preconcentration, harvesting, disruption and extraction methodologies.

Medium- to long-term R&D topics for 2014–22:

- Metabolic engineering in order to develop robust specialised industrial algal strains together with shorter chlorophyll antenna size.
- Devise smart biorefinery approaches for lowering biofuel costs from $CO_2$ and sunlight.
- Expansion of metabolic libraries to allow effective fermentation of the recalcitrant seaweed polysaccharides.

Long-term R&D topics for 2020–24:

- Bioprospection of new sustainable aquatic biomass (microalgae, seaweeds and aquatic plants), selective seaweed (cross)breeding and cultivar selection, as well as gene modification (for microalgae), for novel concepts towards a next generation of low-cost novel molecules for biofuels (jet fuels and others).
- Advanced consolidated bioprocessing for direct microalgae conversion of sugars into biofuels.
- Developing cost-efficient micro-/macroalgae harvesting and product recovery.

# 6. Disruptive thermochemical-based technologies

## 6.1 Power and heat

A wide variety of thermochemical conversion systems has been developed in the past four decades for power and heat applications and many rather exotic conversions systems exist in the laboratory and small-pilot stages. However, really disruptive solutions are difficult to create based on any single conversion technology. Instead, disruptive biomass solutions can be expected to be combinations of different innovative technologies. Some examples are given in the following.

### *6.1.1 Farm- and village-scale power production from multiple renewable sources*

European countryside both in rural and agricultural areas offers good potential for distributed high-efficiency power production. Electricity production can be combined to heating and cooling requirements and different renewable source can be combined in an innovative way. The target should always be to maximise the conversion efficiency of the limited biomass resource. Innovative proposal should be requested from the European R&D organisations and industries. These solutions may include, e.g., the following elements:

- Use of biogas technology for manure and other organic waste.
- Innovative small-scale gasification/pyrolysis technologies for wood residues, short rotation forests, straw and energy crops, use of ash streams for fertilisation purposes.
- Use of advanced gas engines or fuel cells for electricity production.
- By-product heat to be used for drying, heating and cooling purposes.
- Innovative solutions to be made on either on "farm level" or "village level".
- Integration of wind power and solar power or heating into the RESHybrid systems.
- New valuable products and integration of renewable energy production to small industries.

### *6.1.2 Material recycling waste-to-energy plant*

In the future most waste streams will be too valuable to be incinerated and landfilled according to present practice. Waste fractions contain high amounts of copper, aluminium, iron and zinc, which should be separated for reuse in the future economy. Even many critical raw materials (e.g., rare-earth metals, platinum group metals, antimony, cobalt, etc.) are often rich in special waste streams such as electronic and auto-shredder residues. Thermochemical conversions systems can be designed so that recovery of metals is optimised. The carbon-containing organic part of the waste stream can be converted into clean gaseous or liquid fuel, which can be used in high-efficiency power plants, although special attention will need to be placed on management of contaminants.

Innovative R&D projects may focus on some of the following solutions:

- Optimised thermochemical conversion processes utilising slow or fast pyrolysis, gasification and different gas-cleaning methods as primary separation steps for carbon-containing organic materials and valuable recovered metals.
- Innovative separation and reutilisation methods for targeted valuable metals.
- More efficient power cycles for gaseous or liquid fuels derived from waste material.
- Boosting power efficiency by the use of other renewable energies or fuels.
- Use of by-product heat for heating and cooling of urban areas or industries.

The basic gasification or pyrolysis processes do not necessarily offer possibilities for really disruptive technologies. Many rather exotic systems that apply different methods of providing the required energy (e.g., plasma or microwave heating) and various kinds of catalytic gasifiers have been studied but they do not seem to offer any dramatic improvements for overall energy balance. On the other hand, direct use of solar energy to provide heat for endothermic gasification, reforming or pyrolysis reactions is one method which may dramatically increase the biomass conversion efficiency. This technology can be particularly interesting in southern European latitudes. Other examples of disruptive thermochemical conversion systems are high-pressure liquefaction and supercritical steam-gasification processes, which may be interesting methods for converting wet biomasses into transportation fuels, while ordinary gasification and pyrolysis methods are more suited to carbon-containing solid feedstocks.

## 6.2 Transport fuels

### *6.2.1 Solar-assisted thermochemical conversion of biomass to transportation fuels*

Direct solar energy can be utilised in many alternative ways to provide the required heat for thermochemical conversion processes. These systems were studied and evaluated in detail already in the 1980s, but only now have they found really interesting applications in development of advanced renewable fuels for transport. For example, solar-driven allothermal gasification process has a number of advantages: 1) it delivers higher syngas output per unit of feedstock, as no portion of the feedstock is combusted for process heat, 2) it produces syngas with higher calorific value and lower $CO_2$ concentration, and 3) it eliminates the need for an upstream air separation unit, as steam is the only gasifying agent. Ultimately, solar gasification offers an efficient means of storing intermittent solar energy in a transportable and dispatchable chemical form. In a similar way, concentrated solar energy can be utilised for pyrolysis processes and for secondary gasification of pyrolysis oils or reforming of gasification-derived hydrocarbons. The R&D priorities of this disruptive technology field include:

- System development for innovative solar-assisted gasification, pyrolysis and reforming processes.
- Alternative ways of introducing the concentrated solar energy including direct heating and convective systems utilising alternative heat-carried media.
- Identification of different novel integrated concepts achieved by innovative combinations of solar energy and biomass conversion.

R&D could be organised at some of the existing European solar energy platforms.

### *6.2.2 High-pressure biomass conversion into liquids and gases*

In addition to ordinary gasification and pyrolysis technologies, other types of thermochemical conversion systems have been suggested and studied for the production of high-quality liquid and gaseous fuels. These processes often operate at very high pressures but relatively mild temperatures and in the presence of catalysts. These high-pressure conversion systems are in principle suitable for biomasses which are in the liquid state or which can be fed in the form of slurries.

***Hydrothermal liquefaction*** (HTL) is a liquid-phase, high-pressure, medium-temperature biomass liquefaction process. It has been reported to have two major advantages compared to fast pyrolysis: wet biomasses may be used, as biomass is fed to the process as slurry, and the primary product may be more easily upgraded towards transportation fuels. Overall, although it is not a new process concept as such, there is relatively little easily accessible data on HTL available in the public domain. Much more process development and improvement of the major variables (liquid media, catalyst, reaction gas, and process conditions) are needed before scale-up to pilot stage is possible. Pulping black liquor offers an excellent medium for HTL processing as it already includes alkali salts, which act as a catalyst in biomass liquefaction. Production of organic oil from black liquor has been verified previously. Co-processing of other biomass feeds with black liquor offers a process route, which has the potential to increase biomass processing capacity by integrating HTL into existing pulping industries.

***Supercritical steam gasification*** is another high-pressure conversion technology that has been studied rather intensively but which has not yet reached industrial demonstration. This process is also realised at extremely high pressures and consequently biomass feeding is also one of the challenges of this technology. A so-called **mild gasification** process that aims to produce gaseous fuels (primarily methane) under high pressure and low gasification temperatures has also been suggested for wet biomass.

There is a more general R&D need into the development of optimised novel thermochemical conversion methods for wet biomasses, algae and different liquid wastes. High-pressure conversion processes have interesting potential in this field.

### *6.2.3 Gasification and pyrolysis with co-production of (higher value) chemicals*

Gasification or pyrolysis for energy purposes with co-production of (higher value) chemicals is a high-potential thermochemical technology development that may be characterised as disruptive. This co-production route provides the possibility to reduce the costs of the energy products. The lowest hanging fruit may be the extraction of compounds directly from the gasifier product gas (e.g., benzene), but this line of thinking also has the potential to lead to entirely new concepts for the combined production of (high-added-value) chemicals and energy products (transportation fuels, power and heat). These concepts could be characterised as thermochemical biorefinery concepts.

# 7. Disruptive biochemical-based technologies

## 7.1 Power, heat and transport fuels

The main limitation in the production of either first-generation or second-generation biofuels from plant biomass is the low efficiency with which plants convert solar energy into biomass. On average, the energy-conversion efficiency of plant photosynthesis is in the range of 0.1–0.5%, which means that the earth produces far too little biomass to sustain our energy demands. As a consequence, sustainable energy production only seems feasible if we can dramatically increase the conversion efficiency of the photosynthesis process itself. One of the emergent game-changing technologies adopts so-called bio-solar cell (BSC) factories in which photobiological micro-organisms (e.g. cyanobacteria, eukaryotic algae) directly catalyse the conversion of $CO_2$ and $H_2O$ into chemical energy (e.g., fuel) in a single cell.

### *7.1.1 Bio-solar cell factories*

**i) Background and main advantages**
Production of chemical commodities and liquid fuel by means of natural photosynthesis will undergo a step-change in efficiency by the design and synthesis, through synthetic biology, of designer micro-organisms that are optimised to carry out the reaction:

$$CO_2 + H_2O \rightarrow O_2 + \text{alkanes}$$

driven by the sunlight-absorbing machinery of the thylakoid membrane. Such designer micro-organisms, BSCs, will use less than 5% of the incoming $CO_2$ and solar energy to reproduce and the remainder (i.e., more than 95%) will be used for the formation of biofuels (liquid energy carriers) and/or chemical feedstocks like butanol, ethanol, ethylene, lactate, etc. Calculations show that it is likely that in the long run with these cells an energetic efficiency (relative to the total energy from the sun that impinges on the surface of the earth) of up to 15% can be obtained.

Two criteria are likely to enhance the economic sustainability of BSC biotechnology further: The biofuel (1) **acts as a "drop-in" replacement**, in a blend or on its own, which allows uninhibited use with the existing infrastructure for utilisation (distribution, storage, combustion), and (2) is **immediately separated from the process**, which thereby minimises toxicity and allows continuous catalysis without loss of the catalyst due to harvesting.

BSC biotechnology could also play another important role in the future by storing or “peak-shaving” electricity from the grid. The theoretical energy conversion efficiency is even higher, up to 35%, when photo-biological organisms are grown solely with 700-nm light which can be generated by electricity. 3-D photo-bioreactors equipped with infrared light-emitting diodes (LEDs), emitting at ca. 690 nm could be connected to the power grid, which would thereby allow storage of electrical energy in the form of liquid fuel at an estimated efficiency of over 20%, under periods of excess electricity in the grid. Such photo-bioreactors can also be linked directly to large-scale photovoltaic (PV) facilities and result in “photovoltaic fields” that produce liquid fuel(s).

**ii) Main barriers**
Although several examples of the direct conversion of solar energy, $H_2O$ and $CO_2$ into fuels have been demonstrated with a range of potential fuels, the overall efficiency is still far from that required for commercialisation. The main barrier to commercialisation is the overall efficiency of conversion from solar into chemical energy, which must be improved. Several other factors will also influence the overall

cost of the end-product. Here, the cost of enclosed photo-bioreactor systems stands out as a major bottleneck. Other issues include high sensitivity of BSC catalysts to most biofuels (where tested) and risk of contamination in both open and closed cultivation systems.

Current laboratory strains of photosynthetic micro-organisms are unlikely to be ideal for industrial biotechnology, which currently relies mainly on extremophiles in order to operate under extreme conditions (pH value, salt concentration, etc.) and thereby minimise the risk for contamination. A search and evaluation of the utility of novel strains from the natural environment for potential biotechnological use is warranted.

Another main barrier for production of BSC fuels is the low price of fossil fuels. Here, fracking technology can be considered as a "game stopper" for the development of BSC production systems, given that the economic barrier for implementation should be lower relative to systems that depend solely on sunlight. Towards scale-up and production of progressively lower value commodities (like fuel), the use of photo-biotechnology for production of high-value designer chemicals should be promoted in parallel in order to bridge the development towards economically feasible production of low-value fuel.

**iii) Research priorities**

The research priorities for the development of designer cells include:

- **Identification of the most appropriate target compounds**. Are they toxic to the host? Can we construct high-efficiency pathways? Are the compounds easy to separate? Can they be used within the existing infrastructure for distribution, storage and combustion? Is it better to aim for a metabolic precursor or a blending component that exhibits better compatibility with the overall biotechnological process? These questions are best answered with input from diverse fields including engineers of biology, chemistry and engines.
- **Identification of robust phototrophic production strains for bioenergy**. Novel strains of cyanobacteria and eukaryotic algae with superior photosynthetic capacities, resistance to contamination and end-product tolerance may still be found in nature. The ability to engineer such strains and understand their metabolism will need to be considered thereafter.
- **Synthetic biology.** Tools for engineering should be developed and the genetic stability and product tolerance of chosen host strains will need to be optimised to allow long-term production and high product titre. Pathways for fuels or chemical feedstock will be engineered, and the host metabolism optimised, to match the introduced pathways, all with consideration of the above-mentioned constraints, including product yield, tolerance and utility.

At the level of photo-bioreactor design the research priorities include:

- **Design of photo-bioreactors.** Prototypes of photo-bioreactors, both at 10-$m^3$ scale as well as at 1000-$m^3$ scale, need to be developed. Designs should be available that allow optimal exchange of gas and light, while at the same time allowing an efficient product recovery both from the water and gas phases.
- **Optimisation of LEDs.** For the development of 3-D photo-bioreactors, LEDs should be improved with respect to energy-to-light conversion efficiency, with targeted values of ca. 60% and above; These LEDs should be integrated into the photo-bioreactor designs.
- Demonstration of **peak-shaving**. Pilots of PV-photobioreactor fields and grid-integration should be established to deliver proof of concept.

**iv) Timeline**

Long-term R&D topics in 2014–2022:

- Identification of potentially superior algal strains for industrial photo-biotechnology.

- Identification of most appropriate target compounds to match the selected strains and process.
- For any novel strains, understanding metabolism and development of engineering tools.
- Production of designer cells by biological engineering (synthetic biology).
- Photo-bioreactor and process design including LED improvement.
- Production phase 1: Targeted conversion of $CO_2$ into high-value products at ca. 10–20% conversion rate.

Long-term R&D topics in 2020–2028:
- Optimisation of designer cells and photo-bioreactors.
- Optimisation of production processes; production phase 2: Targeted conversion of $CO_2$ into liquid fuels at >90% conversion rate.
- Pilot of PV-photo-bioreactor fields, grid integration and demonstration of “peak-shaving”.

### *7.1.2 Advanced consolidated bioprocess CBPusing lignocellulosic biomass*

**i) Background and main advantages**

Current processes for biorefining lignocellulosic biomass (LC biomass), especially for fuels, are built upon several unit operations, including pretreatment, biomass hydrolysis, and bioconversion, and completed by downstream processing. State of the art process designs use fungal enzyme cocktails to achieve biomass hydrolysis, often combining this operation with bioconversion to achieve benefits from integration. To go further towards integration, it will be necessary to produce the biomass-hydrolysing enzymes *in situ*, which would thus obviate the need for costly exogenous fungal cellulose cocktails. Moreover, to further reduce cost and improve integration, it will be desirable to devise new low-temperature, low-input pretreatments. However, unlike current industrial biorefinery concepts, natural carbon cycling does not exclusively rely on the enzyme arsenals of fungi: in nature, LC biomass is a major component of organic carbon cycling that sustains life on Earth, and micro-organisms (yeast, fungi and bacteria) play key roles in the process of breaking down LC biomass. Other enzymatic paradigms are known, including cell-bound enzyme systems such as cellulosomes and secreted multicatalytic domain enzymes, both of which owe their efficiency to increased synergy between complementary enzyme activities. Moreover, many naturally occurring micro-organisms possess both the ability to hydrolyse biomass and to produce target molecules for industry (e.g., ethanol, organic acids etc.).

When one micro-organism, or two or more compatible micro-organisms that possess both hydrolysis capability and target molecule production capacity are used for biorefining, it is possible to develop a fully integrated or consolidated bioprocessing (CBP), which converts pretreated biomass into target molecules in a single reactor. Likewise, an advanced CBP concept would go even further by using low-energy, low-input pretreatment, thus providing an almost seamless overall process that involved minimum heat exchange and recycling (water, minerals, catalysts, etc.).

**ii) Main barriers**

While advanced CBP is an extremely attractive concept, several hurdles make it unrealistic at the present time. Importantly, no naturally occurring micro-organism appears to combine all desirable features for advanced CBP. *T. reesei* possesses the ability to produce an external cellulase cocktail in exceptionally large quantities, but is a poor producer of ethanol. Conversely, *Saccharomyces cerevisiae* is devoid of any ability to hydrolyse LC biomass. Moreover, while the cellulosome-bearing bacterium *Clostridium cellulolyticum* can both hydrolyse LC biomass and make ethanol, it is intolerant to high ethanol titres and is unable to use pentose sugars. Finally, it is known that using thermophilic micro-organisms for CBP would procure several benefits, including the ability to work at higher biomass density, thanks to the fluidising effect of higher reaction temperatures and the reduced risk of glucose loss (and thus lower ethanol yields) due to contamination by lactic acid bacteria. However, the number of thermophiles suitable for CBP is small since their growth ability is far from industrial micro-organisms and the genetic tools to modify them are scarce compared to model micro-organisms, such as *E. coli* and *S. cerevisiae*.

In summary, the main barriers to CBP are:

- The need for micro-organisms that combine desirable features (biomass hydrolysis and metabolic capability to produce target molecules).
- Insufficient availability of industrially robust (thermophilic) microbial platforms and genetic tools to modify them.
- Lack of understanding of enzyme synergies and definition of principles for achieving maximum hydrolysis with a minimum number of enzymes.
- Better control and exploitation of enzymes complexes, such as cellulosomes.
- The need for strain-engineering tools and strategies to reduce the high sensitivity of many identified CBP micro-organisms to high alcohol titres.
- Lack of innovative, low-input pretreatments that are compatible with near-seamless operation.

**iii) Research priorities for CBP**

- Intensify deployment of '**omics' technologies** (e.g., metagenomics) and **high-throughput screening** to discover and understand naturally occurring LC biomass-degrading systems.
- Increase **understanding of enzyme mechanisms and synergy** on solid substrates at high concentration and low water content.
- Develop new pretreatments that focus on **rupture approaches** which use low-energy mechanical methods, green solvents, heterogeneous catalysts, combined enzyme-assisted strategies, etc. Develop medium-throughput strategies to screen pretreatment compatibility with biological components of CBP technologies.
- Identify and select **robust microbial platforms** and develop genetic and predictive tools required for metabolic engineering or more global synthetic biology approaches.
- Construct **advanced CBP micro-organisms** and develop new industrial concepts, paying attention to sustainability criteria, including safety and ethical issues.

**iv) Timeline**

Long-term R&D topics in 2014–2022:

- Acquisition of new knowledge (study of natural LC-biomass hydrolysis paradigms, search for new micro-organisms, study enzyme synergy and develop new functional models, develop and evaluate innovative pretreatment alternatives).
- Tool development (develop artificial enzyme assemblies, genetic tools and predictive models for target micro-organisms, prototype CBP micro-organisms, integrated process concepts and methods for sustainability evaluation).

Long-term R&D topics in 2020–2028:

- Pilot and demonstration trials of the most promising technologies and concepts.
- Optimisation of production processes: Targeted conversion of $CO_2$ into liquid fuels at>90% conversion rate.
- Pilot of PV-photo-bioreactor fields, grid-integration and demonstration of "peak-shaving".

### *7.1.3 Bio-hydrogen from lignocellulosic biomass*

The use of sustainable hydrogen (both biochemical- and thermochemical-based) for automotive purposes is one of the prime examples in which a new focus is needed beyond 2020. In the longer term, up to 30% of the hydrogen required, as energy carrier for fuel cells but also as reducing agent for advanced liquid biofuels, will be derived from biomass. The utilisation of this hydrogen may be directly in enginelike systems, or indirectly in $H_2$-fuel cells that produce electricity in a mobile device. The known solutions for storage are as a liquid or embedded in some matrices, but a lot of R&D work must be done, particularly on the safety of gas storage for mobile uses.

Various biological pathways are possible for production of bio-$H_2$, from carbon sources by bacteria or by microbial consortia, or directly from light by micro-organisms and/or enzymes. However, the efficiency of biomass use is only optimised if, alongside hydrogen production, other co-products can be valorised in the chemical sector of the bioeconomy.

Currently, all hydrogen research is being addressed in the Fuel Cell and Hydrogen Joint Undertaking (FCH JU), a public/private partnership funded by the EU and the hydrogen-industry.

# 8. Longer term vision: recommendations

Thermochemical and biochemical technologies offer new possibilities for increasing the use of biomass for high-efficiency power and heat production as well as in producing cost-effective renewable fuels for the transport sector. The R&D needs of different individual technologies have been discussed in detail in the previous chapters, and an overview of the long-term vision is given in the following.

## 8.1 Long-term view of the power and heat sector

For many power and heat applications, but also for many biofuel production pathways, biomass upgrading into high-quality bioenergy carriers is crucial to make biomass value chains more efficient and cost-effective. Challenges connected to biomass use must be dealt with at the source and the resulting bioenergy carriers should meet the requirements of logistics and end-use.

Therefore, also for the longer term, evolutionary technologies like torrefaction (solid product), pyrolysis (liquid product) and gasification (gaseous product) are likely to play a dominant role in boosting the introduction of bioenergy, in particular for the power and heat sector.

The following longer term integrative strategies should be developed to enhance the use of biomass in the European energy and fuels markets in the most efficient way:

a) **Farm- and village-scale utilisation of biomass residues, by-products and energy crops**
The European countryside, both in rural and agricultural areas, offers good potential for distributed production of power and feedstocks for the production of transportation fuels. Electricity production can be combined with heating and cooling requirements and different renewable energy sources can be combined in an innovative way. The target should be to maximise the biomass conversion efficiency, targeting zero-greenhouse-gas emissions and creating remarkable income for the stakeholders of the value chain. Both thermochemical and biotechnical (e.g., biogas) routes are enabling technologies that should be developed.

For the transport sector, concepts in which the primary conversion step (e.g., pyrolysis or torrefaction/pelletisation, biogas, ethanol) is developed on the medium scale and final conversion at centralised larger-scale units may offer interesting new options. Possibilities for co-production of new high-value products should also be developed within this market sector. The combined utilisation of biomass sources as a storable RES component together with solar or wind power will also create new possibilities to improve the economics of distributed energy production in rural and agricultural areas.

b) **Large-scale use of biomass and waste for medium- and large-scale power and CHP plants**
The European power sector is in a challenging t situation at present in its transition to a low-carbon society. In the shorter term, direct co-firing is progressing rapidly on the power market. However, co-firing concepts that allow high or even complete replacement of fossil fuels require co-gasification technology development. In this field medium-term R&D should be focussed on using different high-alkali biomass residues and biogenic waste streams instead of the current high-quality pellets or chips, which could also be used to produce higher value products. Concepts that lead to efficient recovery of metals (from waste conversion) or nutrients from agricultural biomass and forest residues should be developed. In the longer run, high-efficiency power cycles (over 45%) such as IGCC or integrated cycles using large gas engines or/and fuels cell, should be developed. In order to maximise biomass utilisation efficiency, innovative combined power and heating or cooling concepts should be developed for energy-efficient

small- to medium-sized enterprises (SME)s in different industrial sectors, large-scale processes and the food industry, as well as for the utility sector. Bio-CCS will offer complementary solutions for reaching European low-carbon targets.

## 8.2 Long-term view for transport sector

In terms of biofuel use, the medium- to long-term picture (based on evolutionary technologies) may not be drastically different from today, due to the lag time necessary to install new technologies for engines and for distribution of biofuels. So the medium-term market will be mainly based on gasoline- or diesel-compatible solutions (the so called “2G” biofuels). However in 2020–2025 the situation will not be exactly the same as today, since some tendencies are already emerging, such as:

- Use of electricity for short day-to-day transportation (from home to work, also short-distance delivery and craftsman tours) in close integration with other uses of electricity in terms of optimisation of the production (“smart grid” evolution).
- Higher flexibility in the use of liquid biofuels in engines (“dual-fuel” evolution, incorporation of alcohols in diesel-like engines, better yield by using the oxygen atoms from alcohols in gasoline-like engines, etc.).
- New ways to produce diesel-like biofuels and jet fuels by biological routes, such as production of hydrocarbons by yeasts, which is already being tested in the laboratory.
- Evolution of long-distance road transportation (trucks) towards a more integrated system with railways, and possibly a breakthrough change in the dual effect of the increase of taxes and the readiness of the technology if shale gas continues to lower the price of liquefied gas: it will take less than ten years to convert the majority of trucks fleet to liquefied gas, possibly with gas-turbine engines (better yield, less pollutant).

More widely, it is expected that a fast evolution from 2G processes to 2G+ processes along with a significant and competitive market increase of sustainable biomass utilisation can be reached by making use of innovative biorefinery concepts that using biochemical or thermochemical conversion routes, or by combining these two conversion technologies. Biorefineries will offer market-tailored production of high-value products and conversion of low-cost by-products and residues to fast growing green-energy markets. New solutions can be designed by concept development assisted by technology, new chemical-based catalysts and/or biocatalysts (enzymes and cell factories).

In the longer term (beyond 2020–2025), sugar-based biochemical processes offer many possibilities for disruptive technologies. The following longer term technological strategies should be developed to enhance the use of biomass for market fuels for transportation in the most efficient way:

- **Biofuels by innovative sugar-based biochemical and chemical processes.** The number of new biofuel molecules produced from biomass by biological processes (e.g., new jet fuel molecules obtained from hydrocarbons produced by micro-organisms) is expected to become much larger than at present. Other technologies for the production of jet biofuels from sugars include chemical condensation processes such as aqueous-phase processing of the dehydration and condensation of alcohols produced by fermentation. Lignocellulosic ethanol can therefore play an important (intermediary) role in jet biofuel production.
- **Biofuels by innovative co-production at existing oil refineries.** The existing oil refineries offer cost-efficient solutions to decarbonising the transport sector, including the road, marine and aviation markets. These new solutions need innovative technology development for dedicated biomass carriers and conversion technologies in this specific oil-refinery environment that combine top-level biomass conversion and oil refining competencies.

- **Biofuels by innovative photosynthetic processes from $CO_2$ and light.** The direct production of electrons by micro-organisms and/or enzymes, in so-called “microbial fuel cells” ($H_2$ route) or “artificial leaves”, respectively. Bio-solar micro-organisms are another game-changing technology for direct production of biofuels and chemicals from $CO_2$ and sunlight at very high (above 60%) light conversion efficiency.
- **Innovative technologies for using algae and other wet biomass streams by using non-traditional bioenergy solutions.** Cultivation of algae that exhibit a long depth of penetration of photons in water is a major breakthrough that opens the way for novel concepts for the fast development of biofuels from algal stored carbon, either in the form of lipids or carbohydrates.

## 8.3 Biomass sustainability and availability for bioenergy

Although this topic was out of scope of the workshop, its importance is evident and any development of European future bio-economy market can only be based on global biomass sustainability principles, directives and standards. Currently, bioenergy sustainability criteria have been introduced to the first stage of European and national considerations and evaluations. Future R&D on biomass sustainability and system assessment should focus on more detailed and specific evaluation of concrete market-driven value chains, both for transportation and for the power and heat markets. The future bioeconomy policies will need the development and use of assessment tools for the various biomass end-uses both for bioenergy and non-energy applications under common sustainability guidelines.

## Summary tables of main R&D priorities and timeline per technology

| EVOLUTIONARY TECHNOLOGIES / POWER AND HEAT SECTOR | | | | |
|---|---|---|---|---|
| **FAMILY** | **TECHNOLOGY** | **TIME TO MARKET** | **R&D PRIORITIES** | **TIMELINE (OPTIONAL)** |
| **Thermo-chemical** | *4.1.1 Integrated torrefaction-densification concepts for woody biomass* | 2016–20 | P1: Densification of torrefied woody biomass<br>P2: End-use validation in combustion/ gasification | 2014–17 Industrial-scale production and industrial combustion/ gasification trials |
| | *4.1.1 Novel torrefaction-based upgrading concepts for non-woody biomass* | 2018–2022 | P1: Blending strategies<br>P2: Incorporate additional processing (e.g., washing) to meet end-user requirements | |
| | *4.1.1 Hydrothermal upgrading concepts* | 2018–2022 | P1: Maximise energy efficiency<br>P2: Effluent processing | |
| | *4.1.1 Upgrading with high-value chemicals co-production* | 2020–2024 | P1: Maximise co-production yields | |
| | *4.1.1 Removal of solids from pyrolysis oil* | 2016–2020 | P1: Hot vapour filtration<br>P2: Other methods | |
| | *4.1.1 Use of bio-oils for distributed power production by engines, turbines, fuel cells and in RES Hybrids* | 2020–2024 | P1: Oil quality improvement<br>P2: Engine development and testing | 2014–2020 Demo trials with improved bio-oils on advanced engines |
| | *4.1.1 Pyrolysis oil production integrated to combined heat and power plants aiming to maximal overall efficiency* | 2018–2022 | P1: Feedstock flexibility issues<br>P2: Improved oil quality | |
| **Thermo-chemical** | *4.1.2 High-percentage <u>direct</u> co-firing in new pulverised-fuel boilers with higher steam conditions* | 2018–2022 | P1: Fuel engineering and milling/feeding strategies<br>P2: Improved diagnostics and monitoring<br>P3: Performance prediction | 2014–2020 Large-scale trials accompanied by detailed diagnostics, monitoring, sampling and experimental assessment |
| | *4.1.2 <u>Indirect</u> co-firing* | 2018–2022 | P1: Coupling of | |

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| | *concepts for challenging, lower-quality biomass feedstocks* | | preconversion with main boiler | |
| | *4.1.2 Integrated biorefinery concepts involving large-scale power (and heat) plants* | 2020–2024 | P1: Co-firing biorefinery residues | |
| **Thermo-chemical** | *4.1.3 Low-grade fuel gasification with novel ash utilisation for large-scale co-firing and standalone power plants* | 2018–2022 | P1: Improved hot-gas cleaning<br>P2: Material recovery from waste gasification<br>P3: Use of ash as fertiliser | |
| | *4.1.3 Novel small-scale power (< 5 MWe) and heat/cooling with over 35% electrical efficiency and over 80% overall biomass utilisation efficiency* | 2018–2022 | P1: Fuel flexible small gasifiers and new gas cleaning<br>P2: Integration with other renewable energy systems | |
| | *4.1.3 Novel high-efficiency power systems with pressurised gasification (>40% electrical efficiency and >80% total efficiency in CHP)* | 2020–2024 | P1: Innovative combined cycle processes<br>P2: Integrated hot-gas cleaning<br>P3: Improved pressurised gasification | 2014–20: Industrial flagship based on present integrated gasification combined cycles (IGCC) with supporting R&D on P2 & P3<br><br>2017–20: P1 |
| **Integrated** | *Combined use of renewable energies (solar, wind, biogas, biomass) on a farm/village scale with maximum biomass utilisation efficiency* | 2018–2022 | P1: New concepts and innovations<br>P2: Small demos | 2014–17:<br>P1<br>2017–20:<br>P2 |

| EVOLUTIONARY TECHNOLOGIES / TRANSPORT SECTOR | | | | |
|---|---|---|---|---|
| **FAMILY** | **TECHNOLOGY** | **TIME TO MARKET** | **R&D PRIORITIES** | **TIMELINE (OPTIONAL)** |
| **Thermo-chemical** | *4.2.1 High-pressure $O_2$-blown gasification with advanced gas cleaning and optimised fuel synthesis (large-scale BTL with >65% biomass-to-fuel efficiency)* | 2020–2024<br><br>(demos in 2018–2022) | P1: High-temperature gas cleaning<br>P2: Gasification at 20–30 bar<br>P3: Improved concepts and synthesis processes | |
| | *4.2.1 Low-pressure indirectly heated gasification followed by simplified gas cleaning for integrated production of fuels, power and heat (overall efficiency >75%)* | 2020–2024<br><br>(demos in 2017–20) | P1: Improved indirectly heated gasifiers<br>P2: Integrated and simplified gas cleaning<br>P3: New concepts for integrated production of fuel, power and heat (CHPF) | |
| | *4.2.2 Catalytic pyrolysis for improving the raw oil quality* | 2018–2022 | P1: Development of new catalysts<br>P2: Catalytic pyrolysis process and oil upgrading R&D | |
| | *4.2.2 Pressurised hydropyrolysis for production of high-quality oil with minimal upgrading needs* | 2020–2024 | P1: Catalyst and process development<br>P2: System integration and final upgrading | |
| | *4.2.2 Use of pyrolysis oil as a co-feed in oil refineries* | 2020–2024 | P1: Concepts with low-cost upgrading | |
| | *4.2.2 Microwave pyrolysis* | 2020–2024 | P1: Valorisation of liquid and gas fractions to optimise value | 2014–2024 |
| **Biochemical** | *5.1.1 Proof of concept for second-generation cellulosic ethanol* | 2014–2018 | P1: Improvements on process intensification (pretreatments, enzymatic hydrolysis, fermentation and product recovery) | 2014–2016: flagships plants on lignocellulosic ethanol |
| | *5.1.1. Lowering sugar costs from lignocellulosic biomass deconstruction* | 2020–2024 | P1: Improved pretreatment methods (e.g., ultrafine milling or ionic liquid pretreatment)<br>P2: Enzyme catalysis of | 2018–2022: First demo plants with third-generation |

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| | | | solid-liquid slurries<br>P3: Plant breeding for increasing biomass quality | technologies |
| | *5.1.1 Enhancement of classical biofuel pathways* | 2020–2024 | P1: Bioprospection novel lignocellulytic enzymes<br>P2: Synthetic biology to improve tolerance of microbial inhibitors | 2014–2022 |
| | *5.1.1 Bioprocess integration* | 2018–2022 | P1: Upgrading lignins<br>P2: Low-energy separation technologies | 2014–2020 |
| **Biochemical** | *5.1.2 Sugars to hydrocarbons* | 2020–24 | P1: Synthetic biology for designing more efficient (current) biofuel pathways<br>P2: Bioinformatics<br>P3: Cost-effective downstream processes | 2014–2020: industrial recombinant strains available |
| | *5.1.2 New biofuels from sugars* | 2020–2024 | P1: Advanced consolidated bioprocessing for new biochemical/chemical routes<br>P2: New catalytic processes for sugar conversions and carbohydrate derivatives | 2016–2020: First demo plant started in operation |
| **Biochemical** | *5.1.3 Oil-based biofuels from microalgae* | 2018–2022 | P1: Liquid biofuels from microalgae using non-fresh water<br>P1: Metabolic engineering for shorter chlorophyll antenna size to increase photosynthetic productivity<br>P3: Cost-effective oil-separation technologies | 2014–2020: First flagship plants in operation |
| | *5.1.3 Direct biofuels from algae* | 2020–2024 | P1: Advanced consolidated bioprocessing for direct microalgae conversion of sugars into biofuels<br>P2: Developing cost-efficient micro-/macroalgae biorefineries<br>P3: Novel technologies for harvesting and product recovery | 2018–2022: Large-scale trials with proof of sustainability |
| | *5.1.3 Designing aquatic biomass for next-generation novel molecules for biofuels* | 2020–2024 | P1: Bioprospection seaweeds and other aquatic plants, including metabolic engineering of macroalgae species | 2014–2020: TRL 6 reached |

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| **Integrated** | *4.2.1 Use of excess electricity or (bio-) hydrogen from other sources for enhancing BTL production* | 2020–2024 | P1: Novel integration concepts<br>P2: High-temperature electrolysis R&D | 2014–2020 |
| | *4.2.1 BTL production with bio-CCS* | 2020–2024 | Concept development and supporting R&D | 2014–-2022 |
| | *5.1.1 and 5.1.2 Upgrading of lignin from biochemical conversion routes* | 2016–2020 | P1: Drying/pelletisation for CHP and other energetic uses<br>P2: Lignin upgrading for nonenergetic uses | 2014–2018 |

| DISRUPTIVE TECHNOLOGIES / HEAT AND POWER & TRANSPORT SECTOR | | | | |
|---|---|---|---|---|
| **FAMILY** | **TECHNOLOGY** | **TIME TO MARKET** | **R&D PRIORITIES** | **TIMELINE (OPTIONAL)** |
| **Thermo-chemical** | *6.1.1 and 6.2.1 Combined use of renewable energies (solar, wind, biogas, biomass) on farm/village scale with maximum biomass utilisation efficiency* | 2020–2024 | P1: New concepts and innovations<br>P2: Small demos | 2014–2020 |
| | *6.2.2 Hydrothermal liquefaction and supercritical steam gasification* | 2020–2024 | P1: Developing new multifeedstock high-pressure conversion processes for liquids and gases | 2014–2020 |
| **Biochemical** | *7.1.1 Construction of biosolar cell factories* | 2020–2028 | P1: Identification of naturally occurring strains of phototrophic micro-organisms.<br>P2: Synthetic biology, construction of designer cell factories producing C2–C5 hydrocarbons. | 2014–2022 |
| | *7.1.1 Integration of biology and materials science* | 2020–2028 | P1: Low-cost and high-efficiency photo-bioreactor designs up to 1000-$m^3$ scale<br>P2: Optimisation of LED technology targeting >60% light-conversion efficiency<br>P3: Production phase 1: Targeted conversion of $CO_2$ into high-value products of ca.10–20%<br>P4: Production phase 2: Targeted conversion of $CO_2$ into liquid fuels of >90% | 2014 –2022: P1 and P2<br>2020–2024: P3<br>2024–2028: P4 |
| | *7.1.1 Grid integration of biosolar energy* | 2024–2028 | P1: Demonstration of “peak-shaving” | 2020–2024 |
| **Biochemical** | *7.1.2 Advanced biological tools for supporting CBP concepts* | 2020–2024 | P1: Accelerate research on natural systems, deploying the full power of ‘omics’ technologies<br>P2: Devise enzyme systems that require the minimum individual catalysts | 2014–2024 |

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| | *7.1.2 Advanced consolidated bioprocessing (CBP) cell factories* | 2024–2028 | P1: Bioprospection and engineering of biocatalysts<br>P2: Use of synthetic biology tools for advanced CBP systems P3: Develop integrated systems suitable for CBP (low energy input and compatible pre-treatments)<br>P4: Proof of concept for different prototype CBP micro-organisms | 2014–2024 |
| | *7.1.2 Enzymatic systems and pretreatments for advanced consolidated bioprocessing (CBP)* | 2024–2028 | P1: Develop new descriptive models for the enzymatic hydrolysis of lignocellulosic biomass<br>P2: Master the conception of multienzyme complexes<br>P3: Develop range of innovative pretreatments adapted to CBP systems and favouring low energy requirements. | 2014–2024 |

## APPENDIX 1: TABLE OF DEFINITIONS

| Acronym | Definition |
|---|---|
| ASTM | American Society for Testing and Materials |
| BSC | Bio-solar cell |
| BTL | Biomass to liquids |
| Capex | Capital cost |
| CBP | Consolidated bioprocessing |
| CCS | Carbon capture and storage |
| CEN | The European Committee for Standardisation |
| CFD | Computational fluid dynamics |
| CFHP | Concepts for integrated production of fuel, power and heat |
| CHP | Combined heat and power |
| CNG | Compressed natural gas |
| DG | Directorate General (EC) |
| DME | Dimethyl ether |
| EC | European Commission |
| EERA | European Energy Research Alliance |
| EIBI | European Industrial Bioenergy Initiative |
| ERA | European Research Area |
| FCH JU | Fuel Cell and Hydrogen Joint Undertaking |
| FP | Fast pyrolysis |
| HDO | Hydrodexygenation |
| HEFA | Hydroprocessing of esters and fatty acids |
| HP | Hydropyrolysis |
| HTL | Hydrothermal liquefaction |
| HVO | Hydrotreated vegetable oil |
| IC | Internal combustion |
| IGCC | Integrated gasification combined cycles |
| LC | Lignocellulosic |
| LED | light-emitting diode |
| LHV | Lower heating value |
| LNG | Liquified natural gas |
| MS | Mass spectrometry |
| PV | Photovoltaic |
| R&D | Research and development |
| RES | Renewable energy sources |
| RES Hybrids | Renewable energy sources hybrid |
| RTO | Research and Training Organisations |
| SET | Strategic energy technology |
| SME | Small to medium-sized enterprise |
| SNG | Substitute natural gas |
| SSF | Simultaneous saccharification and fermentation |
| TRL | Technology readiness level |