JRC Scientific and Technical Reports

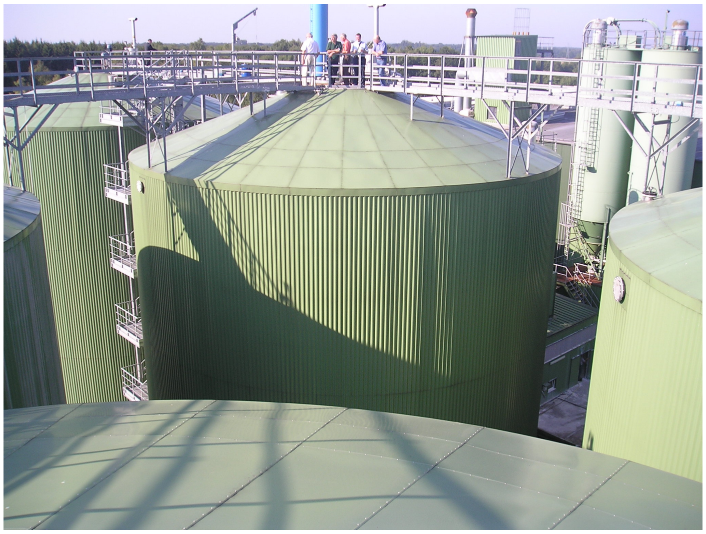
STRATEGIC ENERGY TECHNOLOGY PLAN

Scientific Assessment in support of the Materials Roadmap enabling Low Carbon Energy Technologies

Bioenergy

Authors:
Wolfgang H. Schwarz, Orlando José Gonzalez Bello, Wiebren de Jong, J.J. Leahy, John Oakey, Karin Oyaas, Lars Sorum, Horst Steinmüller

JRC Coordination:
David Baxter, Evangelos Tzimas



EUR 25154 EN - 2011

The mission of the JRC-IET is to provide support to Community policies related to both nuclear and non-nuclear energy in order to ensure sustainable, secure and efficient energy production, distribution and use.

European Commission
Joint Research Centre
Institute for Energy and Transport

Contact information
Address: Westerduinweg 3, 1755 LE Petten, Netherlands
E-mail: david.baxter@jrc.nl
Tel.: +31-22456-5227
Fax: +31-223456-5626

http://iet.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

JRC68050

EUR 25154 EN

ISBN 978-92-79-22680-9 (pdf)

ISBN 978-92-79-22679-3 (print)

ISSN 1831-9424 (online)

ISSN 1018-5593 (print)

doi:10.2790/40833

Luxembourg: Publications Office of the European Union, 2011

Printed in the Netherlands

Preamble

This scientific assessment serves as the basis for a materials research roadmap for bioenergy technology, itself an integral element of an overall "Materials Roadmap Enabling Low Carbon Technologies", a Commission Staff Working Document published in December 2011. The Materials Roadmap aims at contributing to strategic decisions on materials research funding at European and Member State levels and is aligned with the priorities of the Strategic Energy Technology Plan (SET-Plan). It is intended to serve as a guide for developing specific research and development activities in the field of materials for energy applications over the next 10 years.

This report provides an in-depth analysis of the state-of-the-art and future challenges for energy technology-related materials and the needs for research activities to support the development of bioenergy technology both for the 2020 and the 2050 market horizons.

It has been produced by independent and renowned European materials scientists and energy technology experts, drawn from academia, research institutes and industry, under the coordination the SET-Plan Information System (SETIS), which is managed by the Joint Research Centre (JRC) of the European Commission. The contents were presented and discussed at a dedicated hearing in which a wide pool of stakeholders participated, including representatives of the relevant technology platforms, industry associations and the Joint Programmes of the European Energy Research Associations.

Section 1. Technology and System State of the Art and Challenges

Biomass has been used throughout human history as an energy resource, and remains a largely renewable source for energy supply. The EU 20% renewable energy target for 2020 [Directive 2009] has become the main driver for growth of a biomass-based economy. Many different technologies are available to convert biomass into heat, power as well as gaseous and liquid fuels. Its wide range of energy forms makes bioenergy unique. Bioenergy is in principle greenhouse gas neutral as it uses the stored solar energy in plant biomass for energy production and thus converts “CO_2 to CO_2”. Some forms of bioenergy production permits recycling of nutrients to the soil, thereby “closing the loop”. However, the sustainability of each production step, especially the replenishment of soil has to be kept in mind.

The role of bioenergy in the overall energy system requires consideration of both stationary as well as transportation applications (Fig. 1). In this context, the use of biomass is bound to play an important role in (I) transport biofuels, which have the highest employment intensity and offer the largest security of supply benefits, (II) electricity, which provides the greatest reduction in greenhouse gas and (III) heating, which is the cheapest. Biomass and biofuels are storable and deliver energy on demand in small or large independent units. Possible forms of biomass fuels for bioenergy production are:

- solid fuel in either raw (collected/harvested and dried) or semi-processed form (pellets or other more usable form) – for stationary applications,
- liquid or gaseous fuel (e.g. through pyrolysis, gasification, anaerobic digestion) – useful for all applications, some of them including transportation.

In the following section the principle technologies for biomass conversion to energy are described (Fig. 1). The technologies are divided into thermo-chemical and bio-chemical pathways. To get more transparency both are further broken down into pretreatment, first and second transformation and end-product refining (Fig. 2).

In order to realize a substantial market penetration of these biomass conversion technologies, policies should facilitate enlarged biomass production and trading, standards development for novel products, stimulate R&D to develop technology production chains and increase the related system efficiencies through sustainable material development.

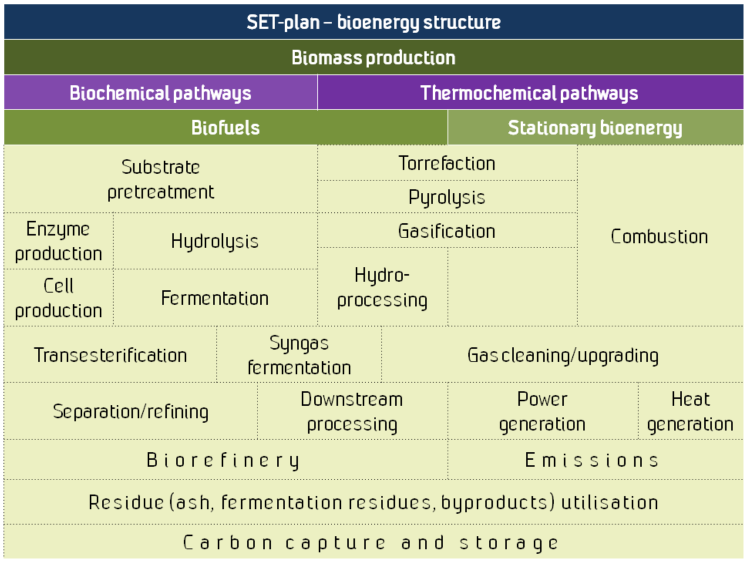


Figure 1. Bioenergy pathways according to the SET-plan

The technologies currently employed for production of bioenergy can be broadly classified into ***thermo-chemical*** and ***bio-chemical*** conversion pathways (Fig. 1). Regarding thermo-chemical biomass conversion, activities include direct combustion, co-firing, torrefaction, pyrolysis, and (co-)gasification. The resulting liquids and gases have to be converted to suitable bioenergy carriers by catalytic or fermentative processes. Bio-chemical conversion includes biomass pretreatment and separation into fractions, hydrolysis of the plant cell wall carbohydrates into sugars, and conversion by fermentation to bioenergy carriers and platform chemicals. The term biorefinery describes the complete conversion of all biomass fractions to useful products in an integrated process scheme using bio-chemical and/or thermo-chemical processes [Kamm, 2006].

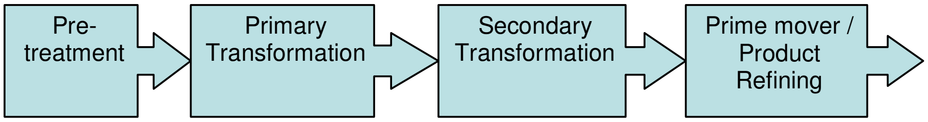


Figure 2. Biomass processing in thermo-chemical and bio-chemical energy conversion systems

As local availability of biomass and associated logistics are usually limiting, except in larger industrial harbour areas, small-scale decentralised processing plants (<<50 MW_{th}) are expected to prevail. In processing schemes with co-utilisation of coal (co-firing, co-gasification) rather large-scale central plants (>>100 MW_{th}) will be relevant [Co-Gasification, 1995].

Thermo-chemical and bio-chemical pathways for energy supply are seen as complementary in future energy scenarios even if in certain cases they are competing for the same biomass feedstock whereas in other cases different niche biomass resources are used. However, they also supplement each other in certain processes, where e.g. residues from hydrolysis or digestion can be burned or used in thermo-chemical conversion processes, or where the CO_2 or syngas is used for *de novo* synthesis of bioenergy carriers through photosynthesis or fermentation. There is a risk of competition with more traditional food/feed/fiber production processes when the same primary sources are used. However, synergies can be created when use is made of the residues of such processes (i.e. second generation biomass).

Research and development of advanced materials in these systems can be divided into materials for i) **structural** use, under demanding and often aggressive process conditions (reactor walls, heat exchanger materials, membranes etc.) in conversion processes and in downstream operations (e.g. gas cleaning, advanced efficient gas engines/turbines, fuel cells) and ii) (multi-)**functional** use such as for mixing and pretreatment devices, additives, separation facilitating media, and catalysts. The functional materials include biological material for biotechnology such as enzymes and microorganisms (whole-cell catalysts) which are usually used in mild, however often aseptic conditions. Increasing process efficiency and intensity through R&D can reduce demand for structural and functional materials, can reduce use of strategic/expensive elements and improve recycling/reclamation.

Not included in this report is the cultivation of the plant biomass itself. It is expected that developments in agriculture will be such that substantial increases in crop yields per hectare will be realised controlling the environmental lifecycle impact. Plant breeding will provide new energy plants with higher resistance to growth inhibitors (e.g. salt), and limited water, fertilizer or herbicide/pesticide utilisation. Use of new plants will reduce the tendency for monocultures and increase sustainability. Lifecycle impact assessment tools will be a very suitable tool to compare the environmental impact of different biofuel generation processes and jointly with lifecycle cost tools to select the best suitable processes. Biomass fuel can be supplied for all conversion processes from a variety of sources, and in a variety of forms. Sources include waste biomass, either from agriculture/forestry operations (e.g. wheat straw) or from the green fraction of municipal or industrial waste and cultivated biomass, and dedicated ‘energy crops’ (e.g. maize, miscanthus, algae, etc.), as well as biomass from the sea (e.g. seaweed). Depending on the quality and composition of the biomass, options for use will be restricted in certain processes, other processes will benefit from smart fuel blending. Not addressed in this report are factors such as the availability of biomass, which depends upon land availability, crop yield, energy density, competition with other users, logistics and reliability of supply and transport costs. These factors will greatly influence the economics and size of bio-energy installations. Centralised as well as decentralized installations will be used taking into account specific regional aspects and different products. In addition, combination of decentralised pre-fabrication and centralised final product manufacturing might be feasible.

This report highlights the material applications in bioenergy technologies. Production of bioenergy has a number of challenges which can be partially solved or improved by new and better suited materials – materials frequently impose restrictions on the application of technologies and their lack hampers progress. On the other hand, improvement of the technologies may have a positive influence on the amount of material needed. This is especially true with the change to bio-chemical technologies which are in general less material challenging.

The following chapters summarize – non exhaustively - technologies for bioenergy production which have a future development potential for substituting traditional, fossil-based energy carriers by renewable sources of energy. Material-based limitations for development of these processes are highlighted.

1.A. Thermo-chemical Processes

This section describes technologies of direct biomass combustion and co-firing to produce power and heat, torrefaction for biomass upgrading, pyrolysis for bio-oil production and gasification to produce product gas or syngas for power and heat applications as well as a chemical feedstock [Werpy, 2004]. These primary technologies are followed by secondary processes which convert the products of pyrolysis/gasification to chemicals and energy carriers via Fischer-Tropsch-synthesis [Dry, 2002] or methanation, after cleaning and upgrading. Also, most important prime movers for power production are addressed with emphasis on impacts of product gas components on materials. The possible capture of CO_2 to effectively reduce these emissions is also briefly described. The bioenergy carriers created through these processes can be further converted by thermo-chemical or bio-chemical approaches.

1.A.a. Direct Combustion and Co-Firing

In direct biomass combustion (both energy crops and residues), the pressure to maintain fuel flexibility while also pushing towards higher efficiency has posed severe slagging, fouling and corrosion challenges for the structural materials used for heat exchange components, most notably the superheaters and furnace walls [Simms, 2007; Spliethoff, 2009; ECSC]. The best available materials used in fossil fuel plants have failed to meet requirements. Significant down-rating of steam conditions has been necessary, even with reduced component-life. As a result, efforts have been made to modify the process environment to reduce its aggressive character through the use of additives and/or blending of fuels. As coal-fired systems offer less aggressive conditions and hence higher efficiencies, co-firing of biomass has been successfully exploited where the damaging components arising from biomass combustion are diluted with the less aggressive coal components. In addition, co-firing can also exploit the benefit of adding S to the Cl-rich biomass combustion products forcing the deposition of relatively benign sulphates products in place of aggressive chlorides. The high content of alkali metals and the high Cl:S ratio in most types of biomass compared to fossil fuels increases operating costs and limits competitiveness.

The ash residues from coal-fired plants are traditionally used for cement manufacture, and therefore have a commercial value. Other uses such as aggregates for civil engineering are also possible with the ashes from some combustion plants. The corresponding residues from biomass fuels contain chemical species (e.g. chlorides) which are incompatible with these uses and so there is risk of reduced opportunity for ash sales when biomass is used in co-firing. It is important to view ash residues as a resource for the recovery of valuable chemicals or for processing into ceramic materials. Where this is not possible, it is still necessary to reduce the impact of ash disposal [van Loo, 2008].

1.A.b. Torrefaction

Torrefaction is a mild thermal treatment, also called ‘roasting’ under an oxygen deprived environment. It is a process targeted at obtaining an improved carbon-enriched solid fuel that has a higher volumetric energy density, is less hygroscopic, more brittle (easy to mill), and not susceptible to biological attack (storable) [Svoboda, 2009; Prins, 2006]. The product is aimed at replacing coal usually in large-scale conversion processes.

1.A.c. Pyrolysis

Pyrolysis is analogous to torrefaction as it is also a thermal treatment process, but carried out at higher temperatures with the aim of producing bio-oil for further up-grading and bio-char for soil improvement. Reduced formation of undesired oxygenated compounds (alcohols, ketones, acids and carbonyls), detrimental for the direct use or further co-processing of the bio-oil, is envisaged [Stöcker, 2008].

A variety of reactor designs (e.g. vertically-oriented fixed beds, horizontal screw-driven beds, etc.) have been developed to suit specific feedstocks and facilitate production of the desired products. High heating rates applied lead to increased bio-oil production, whereas slow pyrolysis rather leads to increased char production (carbonization) [Bridgwater, 2000; ASTM, 1990].

Lignin fractions can be converted to bio-oil using heterogeneous catalysis. The bio-oil quality must be monitored. Novel mono/bi-functional catalysts, such as zeolites, mesoporous materials with uniform pore size distribution, as well as micro/mesoporous hybrid materials doped with noble or transition metals can be used. In addition, the hydrothermal stability of the novel catalysts must be improved. The resistance to deactivation and the catalyst behaviour upon regeneration should be investigated in order to tune new catalyst formulations [Stöcker, 2008].

The high oxygen and water content of lignocellulosic biomass (O/C ratio about 1) leads to problematic bio-oil characteristics like corrosiveness, product instability, immiscibility with crude-oil based fuels, acidity, high viscosity and low energy content. Bio-oils therefore require upgrading if they are to be used as a replacement for transport fuels. Upgrading necessitates the removal of the oxygen and the cracking of the large aromatic structures using catalysts. So far, bio-oil upgrading has been carried out using commercial hydro-treating catalysts, based on transition metal-modified aluminium [Adam, 2006].

1.A.d. Gasification

Biomass gasification can be accomplished using different reactor types suited to different scales of operation, each of them requiring specific structural and (multi-)functional materials [Bridgwater, 1995, 2002, 2003; Knoef, 2005; Neuenschwander, 2005]. Although all reactor classes are capable of carrying out gasification, each of them is a compromise between gas quality, conversion efficiency, suitability for feedstock handling regarding varying physical and chemical properties, the complexity and scalability of design or operation, and investment costs. Fixed bed reactors are suitable for small-scale operation and are restricted to combined heat and power production. The fluidised bed and entrained flow system reactors can be scaled up to the large sizes needed for bio-syngas production for transportation fuels and SNG production, as well as heat and power applications (using gas engines, turbines or in the [near] future fuel cells). Syngas quality is determined by the combination of the feedstock properties, the reactor type and the oxidant used for the process. Oxidants can simply be air (the cheapest option and suitable for small scale systems) or can include other gases such as steam or oxygen where available and where justified by the improved syngas quality. Of these, as for coal gasification, the cheaper production of oxygen using membranes would open up a range of new possibilities for enhanced performance and improved gas quality from smaller-scale systems than is currently viable [Higman, 2003].

Depending on the proposed end-use of the syngas, the clean-up requirements prior to use or secondary processing will be different. Traditional applications for gasification have included making ammonia for fertiliser production, fuel gas for domestic and industrial use (e.g. firing ceramic kilns) and syngas for subsequent processing as liquid fuels (e.g. SASOL).

In all systems where the focus is the generation of electricity and heat, cleaning the syngas presents major challenges, including tar reduction/cleanup, reduction of NH_3 levels, control and disposal of char/ash residues and trace species [Sharma, 2010]. Technology process chains to provide cleaned syngas can include tar cracking, gas coolers, particulate removal and wet/dry scrubbing for contaminant reduction, all of which present challenges for the structural and functional materials used.

Gas coolers often operate with low metal temperatures to avoid aggressive corrosion from Cl-rich condensates at temperatures above 400°C, but also have to be managed carefully in operation/shutdown to avoid acid downtime corrosion. Such coolers are often combined with tar/water condensers to minimise downstream problems.

The removal of particulates from hot syngas using hot cyclones and filtration systems also provide aggressive environments and components can easily become blocked if upstream tar removal is inadequate. Where the syngas is fully cooled and stored before compression and use in an engine, the levels of contaminant related emissions (NH_3) for engine damage should be limited, but the chemistry of the syngas can still give rise to operational problems, e.g. high flame speeds with high H_2 gases, which in turn can lead to material problems for the gas combustion components. Higher temperature gas cleaning and utilization is also possible (usually in higher pressure systems), thus avoiding the loss of the thermal energy in the syngas; such systems have been used with small gas turbines. Fuel cells potentially also offer higher efficiency for power generation and system efficiencies are higher when applying high temperature gas cleaning and upgrading [Aravind, 2009]. However, the filtration materials (metals or ceramics) need to be demonstrated for longer times at the challenging high temperature conditions where there is a significant risk of chemical or physical degradation [Richard, 2010].

Requirements for additional gas cleaning depend on the intended syngas use and the amount and nature of the contaminants resulting from the feedstock and the gasification technology used. Requirements for secondary processing, e.g. to produce hydrogen, are much stricter than for power and heat production using combustion, though for fuel cells they are of the same order [Aravind, 2008; Gupta, 2009; Sutton, 2001].

For wet bio-resources (e.g. sewage sludge), novel process developments include sub- and supercritical water gasification [Matsumura, 2005, 2010]. The extreme conditions prevailing in such processes require the structural materials used to be further developed and tested for long durations [Kritzer, 2004; Richard, 2010].

1.A.e. Secondary Thermo-chemical Processes

Secondary processing of the products from the pyrolysis and gasification steps described above provides a wide range of opportunities for adding value to biomass. In some cases this is essential to provide a useable product (e.g. bio-oil upgrading) and in others it provides options for producing alternative, higher value products.

Upgrading of bio-oils is necessary to enable storage and transport. A combination of water and oxygen content ensures low quality of the bio-oil compared with traditional liquid fuels. In the un-treated state, phase-separation leads to corrosion of containers [Hot Corrosion Standards, 1989] and polymerization leads to increased viscosity to an extent that makes pumping almost impossible. Reduction of water and oxygen content can possibly be achieved by a variety of techniques, including hydro-deoxygenation, catalytic cracking of pyrolysis vapours, emulsification with mineral oil and esterification using alcohol, though none of these processes have been proved at commercial scale.

For the production of liquid products (e.g. transportation fuels) from syngas, catalytic processes such as Fischer-Tropsch synthesis (FTS) can be used [Rostrup-Nielsen, 2004]. While this is established technology, process intensification through the introduction of advanced reactor concepts, such as Microchannel Reactor Technology or Membrane Reactor Technology will lead to significant advantages. The development of micro-structured catalytic reactors (MSCR) incorporating the catalyst or packing of catalyst particles on the inner surface of the micro-channels (e.g. using coating technology) will also provide significant improvements.

From cleaned syngas a variety of gaseous energy carrying fuels can be produced. Hydrogen can be produced either as an industrial chemical or as an energy carrier which can be stored and used for electricity generation or as a transport fuel [de Jong, 2008]. The separation of hydrogen from the syngas also provides an opportunity for the capture of CO_2.

While there is limited experience to date of the implementation of CCS where biomass is the primary feedstock, its difficult characteristics are very likely to lead to unique challenges. In Bio-CCS schemes based on gasification, the H_2/CO_2 separation stages will be influenced by the changed process chemistry. It is likely that the conventional physical solvents used for the removal of CO_2 will prove effective, but the residual contaminants left in the H_2 stream will differ from those in a coal-fired plant. The use of the resulting H_2-rich syngas in a gas turbine or combustion engine will also provide challenges not experienced in coal-fired systems. The impact of the lifetime and performance of the solvents may also prove an issue. In addition, some novel alternative CCS technologies, such as chemical looping combustion or lime carbonation/calcination can be expected to offer benefits with low-S biomass.

To obtain purer H_2 (as an industrial chemical or for use in a fuel cell) the separation of the H_2 from the syngas is required (rather than the separation of the CO_2). This can be achieved using membrane technology – polymeric, ceramic and metallic options exist. The membrane option is likely to be only possible for high pressure gasification processes. While the separation step should lead to a low energy penalty, as predicted for coal systems, compact membrane reactor systems will be needed to be economic due to the large volumes of gas to be handled. The alternative of separating H_2 from low pressure gasification will be possible only if feedstocks giving high H_2 levels are used in combination with cold syngas compression [Phair, 2006]. Once produced the bulk storage and handling of H_2 also presents materials challenges, in particular for transport applications where current storage energy densities are well below those for liquid fuels [Oakey, 2007].

There is also the possibility of simply removing the CO_2 for compression and storage using conventional post-combustion amine systems or oxy-combustion of the biomass fuel. The altered boiler environment if biomass combustion units are oxy-fired could be expected to lead to significantly different deposition behaviour than that seen in coal-fired systems, and as a result substantially altered corrosion behaviour. Further research is required in this area if the potential benefits of bioenergy systems with CCS are to be realised.

Synthetic natural gas (SNG) – as natural gas is a common fuel in industrial and household applications, biomass gasification based SNG would be a very good (short term) carrier to introduce in existing infrastructure. Blending of H_2 and SNG might also be an option but there may be burner operability issues due to the changed gas Wobbe Index. It is also possible to produce Dimethyl Ether, an alternative gaseous fuel, which can be stored in liquid form and needs infrastructure like LPG [Kopyscinski, 2010].

In addition to its use for fertiliser production, ammonia can also be used as a clean fuel in highly efficient solid oxide fuel cells (SOFCs) with low to practically no NO_x formation [Aravind, 2005; Shearing, 2010; Zhang, 2010]. However, there is very limited experience with biomass as original feedstock for ammonia production and this would be required to take advantage of this option.

Methanol is another liquid product from syngas that can be used as biofuel; moreover it is a bulk chemical and formaldehyde is an important derived product. While executed as a high-pressure process when first commercialized by BASF in 1923, most of the methanol is produced at a relatively low pressure (5-10 MPa) and low temperature (220-280°C) process first introduced by ICI. The highly active $Cu/ZnO/Al_2O_3$ catalyst is quite sensitive to poisoning [Chinchen, 1988]. The Lurgi process uses a $Cu/ZnO/Cr_2O_3$ catalyst installed in a multi-tubular reactor, which gives a more isothermal temperature profile, and this is important for achieving high yields of methanol. Most of the methanol being produced in the world is used for formaldehyde production. Methanol is an excellent fuel for spark-ignition engines with a high octane rating, but so far the use of methanol as motor fuel has been limited. Using bio-syngas, cleaning must be performed to a high extent and catalyst materials must be applied in novel reactor configurations and in compositions so as to be selective, robust to poisons and remain active for appreciably long times.

1.A.f Prime Movers and Product Refining

Industrial gas engines and turbines have been developed to use a wide variety of fuels, from natural gas to sour gases and heavy fuel oils. Degradation of materials in such systems has been investigated over the past 40 years. Fuel derived particles can cause both erosion damage and deposition depending on the particle size and composition, component design and operating conditions. As indicated above, there is a wide range of possible gaseous and liquid fuels which could be used in these engines and turbines for mechanical drive and electricity generation. Operational problems can arise if the fuel composition varies with feedstock variability and over time. Fuel-borne contaminants, specific to biomass feedstocks, will also lead to material problems through unpredictable deposition and subsequent corrosion [Oakey, 2004].

Stirling engines and externally fired gas turbines are interesting options for decentralized small-scale combined heat and power (CHP). Material issues here concern mainly the development of efficient and stable heat exchangers (ceramic) and advanced sealing systems to allow substantially higher cycle top temperature and moving parts velocities, avoiding undesired leakages and gas contamination affecting the thermodynamic cycle. Hermetic sealing solution should be also considered for isolating the thermodynamic cycle from the kinematics of the engine thanks to enhanced fatigue resistant materials.

Fuel cells provide high efficiency for electricity production. In particular high temperature fuel cells (MCFC, SOFC) in connection with gasifiers are promising decentralized CHP producing systems. As for combustion engines and gas turbines, the key challenge is to provide suitably cleaned gas as minor contaminants can cause problems with the anode materials [Jörß, 2003].

1.B. Bio-Chemical Conversion

Lignocellulosic biomass from whole plant can be bio-chemically converted to bioenergy carriers in so called "second generation" processes, either using living microorganisms (fermentation) or *in vitro* by catalytic processes (enzymes or catalysts). The bioenergy carriers thus produced are solvents and gases such as ethanol, n- or i-butanol, acetone, methane gas or lipids. They can be used directly or in chemically modified form. To use CO_2 with photosynthesis or syngas with fermentation is another option for producing bioenergy carriers.

Substrates for bio-chemical processes are a wide range of biomass sources such as dedicated energy crops (whole plant) from agriculture and forestry; byproducts and waste from agriculture, forestry, wood, pulp and paper industry, food and feed processing industry; organic household waste or grass, garden and park or road-side cuttings [Antoni, 2007]. Plants with high density, low water content, high growth rate with little care and easy storability and fermentability are preferable but not always available in sufficient amounts (plant breeding). Not all substrates are suitable for all technologies. The substrates often have to be pretreated and/or stabilised for storage. Silage for stabilization needs gas-tight covering materials, process improving additives and inoculants, and acid proof handling equipment. Silage technology for storage of biomass feedstocks has to be improved (e.g. reduced carbon loss, lower sensitivity to oxygen damage).

For fermentation the polysaccharides in biomass have to be hydrolysed by either enzymatic or physico-chemical methods (or a combination of both) to yield sugars. Integration of hydrolysis into fermentation is state of the art (as for the biogas process) or a R&D target (as in consolidated bio-processing). Steel for vessels, stirrers, pumps, pipework, and all substrate handling devices for the fermentation have to be acid resistant (V4A quality (1.4571)).

Fermentation can yield a variety of products and byproducts depending on the fermentative methods applied, the substrates used or the microorganisms inoculated to the process. Separation of liquid products from the usually diluted aqueous fermentation broth is a major issue. In many cases products and process residues can be processed further, bio-chemically or thermo-chemically (biorefinery) [Roussos, 2003].

1.B.a. Pretreatment

Pretreatment represents the central starting point in bio-chemical lignocellulosic biomass conversion, involving the deconstruction of the fibre cell wall. This is accomplished by mechanical, physical, chemical and/or thermal treatment of the substrate [Hsu, 1996; Mosier, 2005; Wyman, 2005]. Use of starch, molasses or sucrose (first generation processes) as the carbohydrate source is state of the art - the sugars are readily available for hydrolysis and/or fermentation. This is not the case for lignocellulosic biomass where the carbohydrates are embedded in the complex lignin/carbohydrate structure of the fibre wall. Several pretreatment technologies have been developed, including steam treatment, acid or alkali treatment, or solubilisation with solvents (e.g. Biosolv process, ionic liquids) [Balan, 2009; Kim, 2005a,b]. Development of energy and cost-effective pretreatment is a challenge in the lignocellulose conversion.

The formation of hydrolysis and/or fermentation inhibitory degradation products during pretreatment is a common problem [Palmqvist 1996, 2000]. Thus material needs involve the development of pretreatment media/solvents giving effective deconstruction of the fibre cell wall and high carbohydrate yields, while causing little or no formation of inhibitory compounds. Furthermore, solvents favouring effective separation of lignin and extractives, leaving a pure carbohydrate stream for further conversion to biofuels, are desirable. Leaving the lignin in a chemically and physically native structure is a challenge to maintain a high value of the material. As raw material flexible processes are desirable, the pretreatment media/solvents should be able to handle a wide variety of lignocellulosic biomass inputs [Yang, 2008].

1.B.b. Hydrolysis

Some pretreatment technologies deliver carbohydrate fractions, which have to be further degraded to mono- or disaccharides suitable for conversion to biofuel in the fermentation process. Carbohydrate hydrolysis can take place using catalysts or enzymes, for which more efficient preparations are needed. Material development is needed for novel enzyme systems from alternative producing strains and for catalysts, as well as advanced solvents in which reaction/separation or hydrolysis can take place (e.g. green solvents, Ionic Liquids). Enzyme screening from natural sources and protein engineering for enhanced activity is a special challenge.

In SSF processes (simultaneous saccharification and fermentation) enzymatic hydrolysis is performed simultaneously with the fermentation process. In such processes the fermenting organism is working simultaneously with the hydrolyzing enzymes, therefore requiring enzymes optimally working in the conditions compatible with the fermenting microorganism i.e. pH and T behaviour. In the so called consolidated bioprocess (CBP) the microorganism is capable of both enzymatic hydrolysis of the substrate as well as fermentation of the sugars are needed (whole cell catalysts). Microorganisms capable of effectively performing both processes simultaneously need to be developed [Cardona, 2007; van Zyl 2007].

Hydrolysis can also take place using strong acid processes or a combination of dilute acid followed by enzymatic treatment. These conversion processes need acid resistant steel reactors, or Teflon or ceramics coated material.

1.B.c. Fermentation

During the fermentation process the liberated biomass sugars are converted to biofuels by microorganisms (usually bacteria or yeasts). Lignocellulosic carbohydrates may contain significant amounts of pentose (C_5) sugars in addition to the hexose (C_6) sugars [Kim, 2005a,b; Liu, 2005; Lloyd, 2005; Mosier, 2005; Teymouri, 2005]. Hexose sugars are easily converted to biofuels by most microorganisms. However, the effective conversion of pentose sugars remains a challenge. Thus, isolation/development of microorganisms capable of effective pentose conversion to biofuels is desirable. Alternatively the use of syngas as a substrate for fermentation of biofuels is possible (e.g. with *Clostridium ljundahlii*).

Development of effective thermophilic fermentation organisms would reduce the needs of cooling media, the risk of contamination by competing microorganisms during the fermentation process, reduce the viscosity of the medium thus facilitating more effective mass transfer processes, as well as facilitate the downstream separation process. Isolation/development of microorganisms that are robust, both with respect to fermentation inhibitors as well as to substrate or product inhibition, represents another favourable advantage. High dry matter concentration in the fermentation process is also desirable as this will give high product concentration and thus facilitate product recovery from the fermentation liquor. This could be achieved by development of novel process layouts involving for example systems aimed at immobilisation of the fermenting organisms by the advanced use of non-fouling membrane systems, encapsulation of the organisms in novel polymer beads, etc.

Effective in-situ product separation is another advantage of advanced fermentation set-ups. This could also represent a step in the direction of a transfer from current batch-wise into continuous fermentation processes which would represent a more effective conversion. Optimisation of the fermentation media (nutrient mixes adapted to the fermentation organism) is needed for fast and effective bioconversion of different substrate inputs [Subramian, 2007].

Ethanol and Higher Alcohols from Biomass

After hydrolysis of the lignocellulosic carbohydrates, the resulting sugar solutions are fermented to alcohol by specialised yeast (research and state of the art) or bacterial strains (research and demonstration plants) [Biofuels Platform, 2009].

Ethanol production from sucrose sugar is a traditional fermentation process, effectively performed using yeasts such as *Saccharomyces cerevisiae*. However the effective conversion of lignocellulosic raw materials, containing various sugar mixtures depend on the raw material input (e.g. C_5 and C_6 sugars) as well as inhibitory compounds formed during pretreatment and so sets new demands on the fermenting organisms (e.g. robust, capable of fermenting C_5 sugars). Thus there is a need to further develop microorganisms capable of effective conversion of lignocellulosic biomass inputs.

n-Butanol/acetone/ethanol fermentation with solventogenic clostridia (ABE fermentation) is a traditional technology, however mostly given up since the 1960s [Schwarz, 2007]. The producing microorganisms are *Clostridium* strains able to utilize non-hydrolysed (starch) or partially hydrolysed (lignocellulosic) biomass and convert C_5 and C_6 sugars [Zverlov, 2006]. Newly (re-)established batch or "continuous" fermentation processes are in pilot and demonstration plants with the substrates molasses (Brazil, China), or starch (China) [Ni, 2009]. Straw or bagasse hydrolysates are in pilot stage (China, US). Isobutanol is produced as a biofuel in a demonstration plant [Gevo, US] from an engineered yeast strain; sugar, starch, and hydrolysed cellulosic biomass are intended for substrate.

Produced solvents are traditionally recovered by distillation. Modern processes involve gas stripping, liquid-liquid extraction, pervaporation, adsorption or membrane separation technology. Separation and rectification technology is most demanding and needs further research on materials (membranes, sorbents). If recombinant bacteria are used in the process, the residual material has to be biologically deactivated or may be used energetically (e.g. for biogas).

In case of pretreatment and hydrolysis for solvent fermentation, complete hydrolysis is not always necessary, depending on the fermenting organism. Clostridia used for the classical ABE-fermentation (n-butanol) process can utilize starch, oligosaccharides from biomass, and pentose sugars. Simple and cheap nitrogen sources can be used. Production of other higher alcohols is in a research state of metabolic engineering of suitable producer organisms.

In advanced fermentation processes a tight sterilisation scheme has to be applied making pressurised fermenter vessels and high volume flow-through autoclaves necessary. The biological and the process parameters have to be controlled at frequent intervals and have to be kept within narrow ranges [Kumar, 2009].

Standardization of bioethanol properties is limited to E85 blends, but there is a need for specifications of E10 and E20, controlling the water content control in order to reduce corrosion effects during the use of biofuels in an engine. Compatibility of biofuels with lubricants, commonly used materials in the engine (e.g. aluminium) and surface treatments (e.g. varnish) should be further studied. Lifecycle environmental assessment of the use of bioethanol will reduce the environmental impact and specially reduce the emission of harmful exhaust gas into the atmosphere. The optimization of the engines when using biofuels and compatible lubricants can increase the power output, one of the limitations when using biofuels in engines.

By-products of these processes are biomass of the fermenting microorganisms (useful for biogas production or as fodder), and – if not separated prior to the fermentation process - lignin-rich material which can be combusted or gasified. Lignin is also a high value raw material suitable for conversion into a variety of value added products for which a lot of research still needs to be done. An effective separation process for the biomass constituents, following the pretreatment step, is a remaining challenge. The separated raw material constituents (such as lignin and extractives) can be further converted to value-added products.

Fermentation broth as well as solid residues (including bacterial/yeast cell mass) are nutrient rich and can be returned to the process, used as feed for animals, or added to biogas plants.

Methane

Biogas production with pure plant biomass became mature at large scale only during the last decade and the process is still not completely understood. The production of methane from pure plant material and the use as a substitute for natural gas was introduced only very recently and is still struggling with difficulties of technology, utilisation of certain substrates and economy if not subsidized [Biogas – an all-rounder, 2009]. However, biogas production makes better use of the carbon in biomass than fermentation due to less CO_2 production than in fermentation to alcohols.

Biogas plants mostly work on a rather small scale (up to a few MW per plant). Existing natural gas infrastructure can be used for distribution and utilisation, e.g. for vehicles running on natural gas or stationary in decentralised small combustion units. The residues are used to replace fertilizer and add to soil structure in an almost perfect cycle. Although seemingly mature, the process still has a great optimisation potential for further increasing yield, retention time, reliability and reduced investment.

Methods for fermenting grass, wood and certain waste materials have been developed and require equipment made from especially abrasion and acid resistant material. The biogas process has to be adapted to relatively pure substrate streams from biorefinery or fermentation processes which have high water content.

For biogas fermentation the substrate material is stabilised for storage by silaging or drying making seasonal crops available year round. Insulation and coating material in fermenter vessels is usually HDPE, but has to be improved for use in thermophilic processes (above 50°C, e.g. with Teflon). Thermophilic processes will gain importance. Concrete for the large fermenters is made according to minimum standards (e.g. class XA3).

Heat transportation with reduced loss (enhanced insulation material) would increase biogas plant efficiency with on-site electricity co-production. The plant size has to be kept small to avoid high costs for feedstock transportation and storage. The average gas yield in operating biogas plants is considerably lower than theoretical potential. Optimisation potential focuses mainly on investment costs, stability and safety of production (optimum process control including online monitoring and advanced on-site analytics), and the quality and hectare yield of dedicated biomass feedstock crops.

Biogas can be produced from bio-waste material other than lignocellulosic biomass such as from animal processing residues (slaughterhouse waste etc.) or hospital waste. This material has to be hygienised prior to or following fermentation by high temperature (well above 55 °C) at least in the first or after the last fermenter step. Alternatively, the process can be run thermophilic (above 55 °C). This reduces health risk by eliminating naturally occurring infectious bacteria but processes running at such temperatures need R&D. Plant investment has to be reduced by replacing existing construction materials with cheaper suitable alternatives.

Biogas produced from sewage may contain siloxanes that can be transformed in internal combustion engines in silicon oxide, generating very hard particles causing abrasion wear of engine components and reducing the lifetime of the engine. Methodologies for eliminating those components before combustion and the improvement of the wear resistance of the engine components are needed.

The minerals contained in the used biomass can completely be recovered (including N-P-K) and used as fertilizer.

Photosynthesis

Photosynthetic microorganisms need only sunlight, water, nutrients and CO_2 for growth. CO_2 from combustion (after cleaning) or fermentation processes can be used (CO_2 sequestration). Macro- or micro-algae, or photosynthetic bacteria (research) can be grown in the sea or in flat ponds, or in transparent pipes or plates. Depending on the type, these organisms can be rich in lipids or carbohydrates that may be used for further conversion to biodiesel (lipids) or bio-alcohols (carbohydrates) by e.g. transesterification or fermentation. As the raw materials are produced intracellularly, the organisms have to be processed to get access to the lipids/carbohydrates (e.g. by homogenisation to open the cell structure) prior to further conversion. Residual biomass can be used as feed for animals or as feedstock for a biogas or gasification process, and for processing to bioenergy carriers (ethanol, biofuels) after hydrolysis.

Production has to be constantly monitored, e.g. for contaminating microorganisms and for optimal light conditions. Harvesting and conversion technologies are challenges as are the low concentration of microalgae in aqueous solution (1-2%) and the shadowing of cells in dense cultures. There is a need for reactor design using the most appropriate materials to facilitate considerably higher biomass density and access to light for growth. The technology today is used for high priced nutraceuticals and possibly can be extended to bulk chemicals and energy carriers.

Artificial (or synthetic) photosynthesis is under research. It uses the application of organic light scavengers on support materials and a water splitting catalyst to obtain hydrogen and oxygen gas [Grimes, 2008]. New materials will be needed here.

Hydrogen

Hydrogen is an excellent energy carrier which can be produced electro- or thermo-chemically, but also advantageously by fermentation or by biological photosynthesis [on Feb. 22th, 2011: http://www.fao.org/docrep/w7241e/w7241e0g.htm]. Its use by fuel cell technology is efficient, its energy content per weight is one of the highest, and its combustion does lead to water and not to CO_2. Its low conversion efficiency during biological production is counterbalanced by low investment and energy costs. Hydrogen is a byproduct in many bacterial fermentation processes such as the clostridial butanol fermentation on sugar substrates [Zverlov, 2006] or during biogas fermentation [on Feb. 22th, 2011: http://www.german-biogas-industry.com/].

Hydrogen production was investigated with photosynthetic microalgae and cyanobacteria. Light energy is used by the photosynthetic apparatus of the cells to split water to hydrogen and oxygen under certain conditions, besides producing carbohydrates and cell mass by taking up CO_2. The containers do not have to be aerated. However, the cells have to be flushed with CO_2 to remove the oxygen produced. Some bacteria produce hydrogen by photosynthesis from organic compounds such as short-chain fatty acids or alcohols with a very high light-conversion efficiency (some non-sulfur photosynthetic bacteria) [February 22, 2011, from http://www.sciencedaily.com /releases/2008/08/ 080825195852.htm]. However, research on micro-organismal hydrogen production is still in an early stage of research.

R&D is needed especially in finding suitable production organisms, in understanding the underlying molecular mechanisms leading to genetic/metabolic engineering, in illuminated containers for photosynthetic production, in avoiding contamination by non-producing organisms, in low tech hydrogen storage, biomass separation and (re-)utilisation at the end of the fermentation process.

1.B.d. Other Fermentative and Catalytic Technologies

Conversion of Sugars for Low Oxygen Containing Products

Current catalytic processes have been tailored for hydrocarbon feedstocks with limited focus on the chemical features inherent in biomass and its derivatives. The catalytic conversion of substrates with low-level of functionalisation such as olefins or alkanes is well developed e.g. for selective hydrogenation. Glucose can be converted to 5-hydroxymethylfurfural (HMF), a valuable platform chemical e.g. for the synthesis of alcanes [Huber, 2005]. Other possible products from HMF with a high application potential are g-valerolacton and alcenes through levulinic acid, butane or pentenic acid [Horváth, 2008; Lange, 2010; Bond, 2010]. However catalytic conversion of biomass and its derivatives requires catalytic transformation in the presence of a high degree of substrate functionality, which will impose processing restrictions. Unlike the petroleum industry where substrates are mostly processed in the gas phase, biomass-derived materials will probably necessitate conversion in the condensed phase, commonly with water as the solvent. This imposes product-specific catalysis technology challenges for biomass utilisation.

A variety of catalysts are used for each process of interest. Using water as part of the solvent/reaction medium and applying mixtures of different sugars are still challenges. Bi-/multi-functional catalytic systems, primarily porous materials with different acidic properties, modified with active metal centers could combine reaction processes avoiding multiple steps.

To date sugars have been converted to organic solvents mainly using simple acidic catalysts providing low product yield and many by-products. New recoverable and environmentally acceptable catalysts, small scale reactors and product separation materials are needed. Novel green solvents, like Ionic Liquids and supercritical CO_2 for product work up could support further developments [Jacobsen, 2010].

1.C. Hybrid Technologies

Biorefinery (BR) is defined as The sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, and/or materials) and bioenergy (biofuels, power and/or heat)" [IEA task 42; Biorefinery, 2008]. Biorefineries are characterised by full utilisation of the multi-bioresource input and the production of a spectrum of useful products with almost no non-utilizable residues. The main processing technologies involved comprise several thermochemical and bio-chemical processes as shown in Annex III, Figure 1. The process conditions for bio-chemical conversion are less severe than thermo-chemical biomass conversion with respect to material challenges [Pinatti, 2010]. However, the (bio-)chemical conversion of the released sugars and by-products (e.g. lignin) to platform chemicals demands that selective and high yield catalysis are applied. Material development here involves catalysts and advanced solvents in which reaction/separation can take place (e.g. green solvents such as Ionic Liquids).

The integrated BR technologies are clean with recovery of energy and reuse of water, acid and effluents, and apply the principles of Green Chemistry [EPA, US]. BR maximizes simultaneous production of food, electric energy, liquid fuels and chemical products and some materials, achieving a competitive position with conventional and fossil fuel technologies [Ohara, 2003].

Section 2. Material Supply Status and Challenges

Material challenges increase with the complexity and composition of the feedstock if biomass is used instead of fossil fuels. However, the challenges decrease with the advance of process development, the use of new, advanced materials, and the change to biotechnological processes; these gradually replace inorganic material with biological and bio-chemical material, and for instance use enzymes instead of catalysts, or fermentation instead of thermo-chemical treatment with Fischer Tropsch Synthesis. Many of the challenges for structural materials are also faced by the fossil sector, but the challenges when using biomass are usually greater because biomass results in more aggressive process environments.

This section reviews the materials challenges in the technologies highlighted in Section 1, dividing these by the type of material in question.

Thermo-chemical Processes

Structural Materials – Alloys, Coatings and Ceramics

- For biomass-fired combustion systems, the balance between mechanical (pressure containment) performance and corrosion resistance is very different to that for fossil fuel plants, and so the materials approach to improve component lives have been focused on surface coatings/weld overlays to extend component lives. With boiler design codes based on fossil plant requirements (e.g. creep rupture life) rather than corrosion resistance, the use of coatings and overlays on these proven substrates have proven the preferred option. Even where more resistant alloys, such as Alloy 625, have been approved for furnace wall use, performance has not been sufficient to allow significant improvement in steam conditions. While it seems unlikely that a new alloy with significantly improved characteristics for biomass combustion plants will be found, the focus should be on developing durable but affordable substrate/coating systems which are sufficiently rugged and repairable to meet plant requirements [Sims, 1987]. Modelling of materials performance and reliable monitoring systems are also required.
- Ferritic and austenitic steels will continue to be the main structural materials used in thermochemical conversion systems, while Ni-based alloys will be used in associated gas turbine technologies. In all cases, the use of protective coatings will increase in importance. Challenges for future production of these materials are:
    - availability of transition metals used in advanced steels and Ni-based alloys, in particular Ni itself. Mo, Cr, Nb, Y, V, Mn, and Co are critical elements.
    - availability of coking coal and iron ore for steel production; supplies are controlled by a limited number of suppliers.

  In addition, high strength wear resistant alloys, hard facings and coatings are required for biomass cutting, handling and pre-processing equipment.

- In addition, improved understanding of the combustion, pyrolysis and gasification environments should lead to improved blending or additive-based strategies [Khan, 2009], reducing the damage potential in systems where fuel variability does not over-ride the validity of this approach, leading to excessive additive requirements. In such circumstances, co-firing with a benign fuel (not necessarily coal) is the preferred approach.
- In cooling the syngas from biomass gasification (or extracting heat as steam for other process uses), similar material solutions (e.g. the use of Mo-containing alloys such as Sanicro 28) to those applied in combustion systems are used. Experience with coatings is limited and little success has been obtained, although this option remains worthy of further exploration. However, improved steam conditions and durability are most likely to be achieved through the combination of improved materials with a better understanding of the syngas environments combined with process/materials monitoring.
- One of the current challenges in gas cleaning for biomass (and coal) gasification is to extend the life time of both ceramic and metallic materials used for filtration while maintaining their cleaning performance in effectively dedusting syngas at high temperatures. A wide variety of metals and ceramics such as FeCralloy, Iron Aluminide, SiC, fibrous alumina-silicates, etc have been tried but all

have limitations either in their ability to resist the thermal cycling or corrosive environments (e.g. alkali species) in these filtration systems or their high cost. Opportunities exist to combine filtration and catalytic conversion to provide smaller, process-intensified units.

- Improved filtration and gas cleaning to remove NH_3/HCN, H_2S/COS, HCl and certain other contaminants (e.g. alkalis) and trace elements is required is required for combustion engine, gas turbine and fuel cell applications. Testing is required to ensure that the current approaches for reducing/removing these species are suitable for the likely range of biomass feedstocks.
- Secondary processing for the production of transportation fuels provides a number of material challenges in order to develop advanced FTS reactors based on the Microchannel Reactor Technology [Tonovich, 2008] or Membrane Reactor Technology [Rohde, 2005]. These will require special stainless steel alloys to avoid *carburization* [Grabke, 2002] and *metal dusting* [Nishiyama, 2006]. In addition, porous metallic supports (special steel alloys) and ceramic supports FTS membrane reactors.
- Corrosion of combustion engines and gas turbines using biomass-derived gaseous and liquid fuels can result from the combined effects of gaseous species (e.g. SO_x and HCl) and deposits can form by condensation from the vapour phase (e.g. alkali and other trace metal species) and/or from particle impact and sticking. This is particularly true for systems where warm or hot gas cleaning is employed (to achieve increased efficiency) where contaminants may pass through the engine/turbine. Improved protective and thermal coatings, designed to resist the specific contaminants likely to pass through the gas paths of biomass plants are required. Combined with this are improved monitoring and modelling capabilities to determine material condition and predict service lives.
- Thermally efficient and stable heat exchangers are required for the successful implementation of stirling engines and externally fired gas turbines using biomass-derived fuels. To date, these options have proven uneconomic with coal-derived fuels due to high temperature strength and corrosion issues. To achieve the very high levels of performance required, metallic materials with enhanced high temperature strength (possibly using oxide-dispersion strengthened alloys), with specialised coatings to give corrosion resistance and/or ceramics (e.g. SiC:SiC fibre reinforced materials) are needed.

- High temperature resistance materials for seals and sealing systems such as reinforced polymers and polymeric composites are required in order to improve sealing efficiency and subsequently the thermodynamic cycle efficiency. High temperature and high sliding velocity material are required for enhanced sealing performance. Chemical compatibility of these materials and resistance to permeability is required in order to avoid destructive phenomena like explosive decompression and leakage.

Functional Materials – Catalysts, Bed Materials and Membranes

- The increased level of flue gas, with high NO_x levels and ever tighter emission regulations also increase the demand on catalytic de-NO_x systems. Improved, poison resistant catalysts are needed that have favourable life cycle characteristics [Dai, 2008].
- The bed materials used for fluidised bed combustion and gasification technologies have the potential to be multifunctional, altering the chemistry of the gaseous products and reducing levels of contaminants, e.g. reducing tar, sulphur and alkali species. In chemical looping systems aimed at CCS or H_2 production, they can also provide oxygen for the process. Durable and mechanically stable O-carrier bed materials are required for these applications. It is not clear whether the oxides and other materials currently used for this purpose will be adaptable to biomass-based systems.
- H_2 storage materials with increased energy density for transport applications, e.g. light element hydrides.
- The acceptance level for catalyst poisoning should increase, catalysts should become cheaper, and catalyst cleaning/regeneration methods should be improved.
- Development of effective reactor, catalyst as well as solvent systems represents remaining challenges in thermochemical conversion. Fischer-Tropsch synthesis, DME and methanol synthesis are critically dependent on the quality of the catalysts involved. Development of effective solvent systems is also critical for efficient thermo-chemical conversion (e.g. solvolysis, pyrolysis) of biomass/biomass constituents.
- The de-oxygenation and de-carboxylation reactions for the upgrading of bio-oils require durable catalysts [Stöcker, 2008]. Porous materials (e.g. zeolites, mesoporous materials, etc.) offer significant potential as catalytic materials for these processes. However, the hydrothermal stability and resistance

to deactivation of the catalysts need to be improved. The introduction of tailor-made porous catalysts should result improved product quality, with fewer undesirable compounds/by-products due to the shape-selective effect of the porous catalyst and improved catalytic behaviour.

- Improved catalysts for pyrolysis would allow lower temperature, thereby reducing energy costs.
- Besides catalyst development, reactor concepts are important: Upgrading is mainly done so far in fixed-bed systems at 340-500°C, however, large amounts of carbonaceous deposits can be avoided by applying a mobile catalyst phase.
- For the downstream catalytic production of transportation fuels using FTS the key functional material challenges are:
    - Improved FTS catalysts and manufacturing methods based on the design and preparation of active, selective and stable catalysts for selective production of specific biofuels and chemicals.
    - Development of micro-structured catalytic reactors (MSCR) incorporating the catalyst or packing of catalyst particles on the inner surface of the microchannels (e.g. using coating technology) .
    - Deep desulphurisation of bio-syngas prior to catalytic upgrading to transportation fuels [Meng, 2010]. Demonstration plants for FTS based on the Chemical Process Intensification principles using small modular reactors (SMR) are required [Reay, 2008].
- The low-cost production of O_2 using selective membranes for use in biomass gasifiers and the oxy-combustion of biomass is required to support the development of these options (similar to their fossil fuel equivalent processes).
- The separation of H_2 from syngas presents significant materials challenges as there is a need to develop cheap, effective membrane materials for separation from bulk CO_2 after well-cleaned biosyngas has been shifted to optimize H_2 production. These may be separate for the shift reactor or could be combined with the catalyst used there.
- Material issues for the use of DME are development of cheap, selective and stable catalysts to convert syngas to this compound.
- For SNG production from biomass gasification, cheap, selective and stable methanation catalysts are required in view of the peculiar biomass derived syngas composition.

Ash Residues

- Thermochemical conversion, in particular (co-)combustion and gasification leads to production of a mineral rich by-product - ash. The common use of this ash in cement production demands composition restrictions on carbon content and ratios of certain mineral species. The secondary treatment of ashes may be required to maintain this application for biomass derived ash materials.
- Leachability of trace elements is an issue for the disposal of ash materials.
- In the future, it is likely that ash will prove a valuable resource for certain high-value elements (e.g. Phosphorous). Processes for the extraction of such elements are needed.
- In pure biomass conversion technologies, returning *crucial nutritional* elements back to the fields and forests should be implemented in the biomass conversion chain.

Bio-chemical Technologies

The increasing efficiency, productivity and yield of the processes and the scaling down of the equipment are reducing the amount of material to be used. Many technologies used in bio-chemical conversion depend on new materials such as corrosion-resistant steel, Teflon or ceramics coated containers and pipework, novel catalysts, separation membranes or nanoparticles. Challenges are subject to research in the following fields:

- A wide range of biomass substrates is possible. However, only few substrates are actually used in pilot and demonstration plants for biofuel production and R&D is needed for widening the substrate basis. Bio-chemical fuel production needs R&D for optimal substrate mixture selection and for inclusion of substrates such as grass or straw, woody material or certain wastes which contain or produce substances toxic for the bacterial flora in fermentations or are not sufficiently accessible for the degrading microorganisms or enzymes.

- Development of cost- and energy efficient pretreatment and separation schemes that aim to optimize utilisation of the raw material input are needed. A major challenge is to ensure that all biomass input components as well as by-products are utilised in an optimal way. Pretreatment schemes ensuring optimised use of the biomass are currently under development. Raw material flexibility, minimum inhibitor formation, as well as maximum carbohydrate yields are central targets. The fate of lignin and hemicellulose are important challenges. Processing has to avoid unfavourable conditions for sugar re-formation (back-reaction), chemical derivatisation (pentoses to furfural, lignin to sulfo-lignin, formation of lignin-carbohydrate complexes) and physical change.
- To improve enzymatic hydrolysis efficiency, cheap ways of production (enzyme production on site without enzyme concentration and purification) and new, more efficient types of cellulases are being studied, such as bacterial enzyme complexes. The precondition is a dramatically improved technology for enzyme screening and production of heterologous recombinant proteins using new genetic material. Screening for new enzyme activities is severely hampered by the lack of a range of host organisms with available genetic tools. For a systematic search for new, effective thermophilic cellulolytic enzyme systems, new platform organisms for protein expression and genetic engineering have to be added. Possibilities for enzyme reutilisation are also being studied, e.g. by applying novel magnetic nanoparticles (small size) loaded with enzymes. Heterologous expression of recombinant multimodular enzymes at large scale is a major challenge. Research into modification of alcohologenic strains for polysaccharide degradation in one vessel (“consolidated bioprocessing”) is on-going.
- There is no theory of synergistic enzyme activity on insoluble substrates/surfaces which hampers progress towards material savings through improvement of hydrolytic enzymes by protein engineering.
- The simultaneous utilisation of pentose sugars by highly effective industrial yeast strains is still a challenge. The tolerance of ethanol producing bacteria for high substrate, inhibitor and product concentration needs to be improved. Alternative alcohol producer organisms such as yeasts, Escherichia coli, Klebsiella oxytoca, Lactobacillus sp., Clostridium sp. and others are developed for the simultaneous utilisation of all sugars (pentoses as well as hexoses) in continuous fermentation.
- For newly isolated species and strains, genetic systems have to be evaluated and developed.
- Alcohol producing strains with the ability to hydrolyze the polymeric substrates are in the pipeline. A major challenge is the metabolic engineering in industrially successful yeasts and in promising bacteria, especially regarding the redox balance and carbon flux. High end product concentration and selectivity, and insensitivity for inherent and generated inhibitors and process conditions are major goals.
- In biogas, research is being performed to increase the methane to CO_2 ratio of the biogas through optimisation of the feedstock mix and regulation of the active bacteria. Of importance is reduction of ammonia and hydrogen-sulphide for which removal technology has to be improved by new sorbents or catalysts.
- Automatic supervision of the fermenters has to be improved using novel sensor and monitoring equipment for gas quality and composition, for pH and FOS/TAC value, for acidity and acid content (acetic and propionic acid), for trace elements, and degradation value. The monitoring methods have to address the composition and change of the microbial community, and advanced monitoring techniques for quick and cheap results are needed.
- Multistage or plug-flow fermenters as well as new concepts for biogas fermenters are in development and will partially demand new materials. High consistency processes are needed to ensure high product concentration.
- In addition, small scale biogas plants with simplified automation for the use of liquid manure have to be developed especially for use by farmers. For these plants also new vessel and pipe materials mainly derived from plastics will be necessary.
- Downstream processing technology for end product separation and rectification are a permanent research subject. New membranes, sorbents and solvents will be necessary.

Catalytic conversion to chemicals:

- Bi-/multi-functional catalytic systems giving high yields in aqueous systems. Development of catalytic processes for highly functionalised biomass substrates in aqueous media and ideally coupling of these systems with separation processes.

- Transition metal modified mesoporous materials are currently under investigation for the dehydration of sugar mixtures in water. Other options include continuous catalytic processes which can combine dehydration with hydrogenation or condensation in a one-pot reaction or in a continuous system.

Hybrid Technologies:

- A challenge for biorefineries is to apply process intensification [Reay, 2008] targeted at high yield, selective production of a dedicated product spectrum. This requires development of catalysts, e.g. for combined hydrolysis/dehydration reactions under comparatively mild conditions. Utilisation of all useful mineral matter is required. A particular example is phosphorus. (see Figure 1 in Annex III)

Material supply status and challenges could be identified:

Structural Materials – Alloys, Coatings and Ceramics

- Pretreatment is crucial for complete substrate utilisation. Grinding, cutting and chaffing of biomass are often subjected at high pressure/temperature under acidic and abrasive conditions, making special steel necessary [Talebnia, 2010].Hydrolysis technologies using diluted or concentrated acid under heat and pressure demand special materials such as Teflon coated or ceramics equipment resistant to these conditions.High-tech fermentation relies on pure cultures, partially genetically modified microorganisms and requires sealed, pressurised vessels and equipment of highest quality material. Tailor made process technologies for small scale operation have to be developed with yet unknown demands for material.High volume autoclaves for substrate slurry are another challenge as are large sealed, pressurised fermenter vessels (>400 m^3, preferably wide not high) [Zverlov, 2006].

Functional Materials – Catalysts, Enzymes, Membranes and Sorbents

- Processes suitable for the effective hydrolysis of lignocellulosic carbohydrates must be developed. Novel enzyme mixtures and producer strains for large amounts of recombinant proteins must be developed. Alternatively novel microorganisms capable of simultaneous hydrolysis and fermentation (CBP) need to be developed.
- More natural organisms have to be screened to identify appropriate strains of bacteria or yeast (microbes), or to isolate genes with more appropriate enzymatic or metabolic functionality that will enlarge the substrate basis and product range, and increase production efficiency, as well as decrease the amount of material needed.
- Downstream processing of products involves advances in membrane or adsorbent technology. A challenge is the separation of higher alcohols from water. There is a need for membranes with high removal capacity of product (NOT water) e.g. for pervaporation, or suitable absorbents.
- New inorganic and organic sorbents are needed for energy-efficient product separation from diluted aqueous solutions or from gas streams especially in fermentation, for solvent purification, or for removal of sulphur or ammonia from flue gases; they could provide increased process efficiency and cost reduction. For smell reduction, and sulphur or ammonia removal in smaller scale, biological processes using microorganisms can be developed.
- Indirect downstream effects such as biofuel (e.g. E10) interactions with engine lubricants can lead to undesirable effects on engine components. The engine oils working with biodiesel or biodiesel/bioethanol mixtures are diluted with the biofuel. The cause of these effects and possible solutions improving the compatibility of the oils with biofuels should be analysed. There will be a need to ensure that quality of new fuels and new fuel blends is taken into account in future biofuel production. The fuel quality has impact on engine performance and is a possible cause of downstream materials problems, but a detailed assessment is outside the scope of the bioenergy report. The challenges of using biofuels (bioethanol, biodiesel) instead of petrol/diesel, are a considerable reduction in CO and HC emissions. Difficulties are the reduction of power in the engines, a slight increase of NOx emissions and risk of higher consumption. A further collaboration between engine builders and biofuel manufacturers is needed in order to optimise the engines working with biofuels. Compatibility of materials with biofuels is another issue due to a higher content of water; materials with a higher corrosion resistance are needed.

Section 3. On-going Research and Actors in the Field of Material Research for Energy Technology Applications and Challenges

For the thermo-chemical technologies as well as the bio-chemical technologies the ongoing research is mentioned in Section 2 together with the material challenges in the single technology fields. It is summarised in Annex III table 1 for the structural material priorities, and table 3 for the functional and process material priorities.

Table 2 lists the major technology priority areas for the structural materials in 1. reducing time to market and life cycle costs, 2. higher performance in harsher environments, and 3. improved life management and reliability. Technical challenges, key applied R&D needs, key fundamental R&D needs and key supporting R&D needs are listed. A similar list is presented for the functional and process material priorities in Table 3, with 1. improved performance of reactors and process systems, 2. disposal or utilisation of residues, and 3. improved life management and reliability.

Some examples of projects within FP6/7 (cooperation, infrastructures) and other EU and national programmes are summarised in Annex III table 3.

Annex III Table 4 lists actors in the field of material research for energy technology applications and challenges sorted alphabetically within an EU member state. This list is not exhaustive and it was not possible to get information from all EU member states.

MATERIALS CHALLENGES & RESEARCH PRIORITIES

The main challenges are summarised below.

Structural Materials for Plant Components

- boiler materials with high resistance to corrosion (e.g. halide corrosion)
- supercritical or ultra-supercritical steam components for high efficiency power plants (e.g. nickel-base alloys that are being developed for high efficiency fossil fuelled power plants)
- improved repair and maintenance techniques for reactors, heat-exchangers, pipework, etc. (e.g. improved repair coatings)
- improved remnant life assessment techniques (leading to higher plant availability)
- protective coatings for gas turbines working with bio-syngas, including H_2-rich gaseous fuel (metal/ceramic coatings derived from turbines using fossil fuels)
- long-life high temperature fuel cells working with bio-syngas
- improved temperature resistance of linings for thermophilic biogas reactors
- acid resistant vessels for biochemical pre-treatment of biomass (e.g. acid resistant steels and/or coatings)
- High temperature resistance materials for seals and sealing systems like reinforced polymers and polymeric composites are required in order to improve sealing efficiency and subsequently the thermodynamic cycle efficiency.

Comments:

(1) Many of the challenges for structural materials are also faced by the fossil sector, but the challenges when using biomass are usually greater because biomass results in more aggressive process environments.

(2) The move towards clean, de-carbonised fuels will inevitably mean greater use of H_2 as a fuel in gas turbines and fuel cells.

Membranes and Filters

- new membranes for low-cost oxygen production (oxyfuel processes)
- low cost gas cleaning (e.g. hot cleaning of syngas to reduce energy losses; up-grading of biogas)
- new filters for dust removal (e.g. achieved with low pressure drop)
- new solvent separation technologies (e.g. for fuel purification)
- anti-fouling materials for membranes (new materials and coatings needed)

Comments:
(1) There is a multitude of opportunities where membranes and filters need improvement, each providing for increased process efficiency and cost reduction.

Catalysts

- de-NOx catalysts operating at low temperatures (avoiding gas reheating)
- high performance Fischer-Tropsch Synthesis materials resistant to degradation
- increased efficiency of biomass hydrogenation and degradation
- effective hydrotreating of bio-oils for stabilisation
- high performance in-bed catalysts for fluidised bed systems (e.g. in gasification, primary gas treatment to minimise the need for downstream cleaning)

Comments:
(1) Major research effort needed on catalyst efficiency, resistance to degradation and regeneration of catalysts

Enzymes (including new screening systems)

- better enzymes for hydrolysis pre-treatments
- enzymes producing higher conversion efficiency and better selectivity
- low cost enzymes

Comment: Large effort needed to improve enzyme characteristics, product yield and cost.

Microbes

- increased processing kinetics of substrates (enabling smaller processing vessels and shorter process times)
- improved fermentation selectivity and yield
- new strains of microbes from nature
- new strains for heterologous production of enzymes

Comments:
(1) Large effort needed to develop new microbes for biochemical processes; the field is relatively new and realistic potentials are not yet known.
(2) There is a possibility for microbes to be used for thermochemical processes such as gas cleaning, particularly for sulphur removal. However, the kinetics of biological cleaning would unlikely match the high flow rates of thermochemical processes.

Sorbents

- greater efficiency of sulphur removal at primary stage of processes
- solvent purification and separation
- flue gas cleaning efficiency

Utilisation of Residues

- mineral recovery needed to preserve raw materials stocks, e.g. phosphorous recovery from both thermochemical and biochemical processes
- utilization of combustion ashes as fertilisers and sources of minerals
- spent catalysts recovery
- fermentation of sludges and recovery of valuable metals
- lignin valorisation needed in place of use as fuel for heat
- reducing hazards of wastes that cannot be further utilised

Comments:
(1) Major effort needed for recovery processes for phosphorus
(2) Large effort needed for regeneration of catalysts
(3) Large effort needed on nutrient recycling
(4) Major effort needed to use low-temperature process waste heat

Section 4. Material's Specification Targets for Market Implementation in 2020/2030 and in 2050

4.1. Specification targets for Market Implementation in 2020/2030

Economic Considerations

Many different products also for energetic purposes can be produced from biomass. Only some of the bioenergy producing technologies are economically viable to date, i.e. in the state of development they could be applied. Processes used currently under the present economic conditions are: combustion and co-combustion of biomass with coal (such as wood chips, sawdust, straw), first-generation bio-ethanol and bio-butanol (starch feedstocks, beat-sugar/molasses), bio-diesel (rape seed oil), and biogas (heat and power co-production, enriched methane to gas grid). Pilot and/or demonstration plants exist for second-generation bio-ethanol from straw (pretreatment and enzymatic hydrolysis) and wood (component separation), and gasification (syngas) and FTS to diesel. All other technologies mentioned are in a research or technical state of development.

Economic feasibility of future processes is difficult to calculate and depends on considerable further R&D, especially in the fields of catalysis, enzymatics, feedstock hydrolysis, metabolic engineering, product separation and cleaning, and process engineering (see attached file “Recommendations” and Annex III tables 1 and 2). Today, most of the processes, which convert biomass to energy, are only competitive with fossil fuels if they are subsidized. The following table shows the percentage allocation of raw material, yearly capital and operating costs of some of the above described processes. It can be seen, that the main cost drivers are the operating costs, followed by the capital charges. The raw material costs play a minor role, even if agricultural and forestry products are directly used as feedstock. This means that emphasis should be given to the reduction of the operation costs in terms of promoting energy self-sustained processes in order to reduce the total consumption of electricity, high pressure steam, process heat and cooling water etc. Auxiliary materials such as catalysts should be recycled and capital costs can be reduced with better process performance based on maximised conversion efficiencies, cheaper equipment materials and learning curves in process operation and development especially for second generation technologies. Better understanding of the processes, easier automatic control as well as cheaper and more viable (inorganic, organic and biochemical) catalysts will be the key-factors. Comparative lifecycle environmental assessment studies combined with lifecycle cost will help to assess the sustainability and market implementation of different biofuels technologies.

Fuel	Raw material cost	Capital cost	Operation & maintenance
Fischer-Tropsch-diesel from wood/lignocellulose	12%	32%	56%
methanol from wood/lignocellulose	15%	33%	52%
ethanol from sugar cane	19%	13%	68%
synthetic natural gas (SNG)	22%	28%	50%
ethanol from straw	30%	29%	41%
biogas from municipal waste	0%	45%	55%

Table 1: Cost splitting for production of several bioenergy carriers. Source: own calculation mainly based on Hamelinck [2006] and Müller-Langer [2008].

4.1.A. THERMOCHEMICAL TECHNOLOGIES

For the period up to 2020/2030 a key parameter for market development is certification and standardisation of biomass feedstocks. For example for torrefaction pellets, there are currently no standards at all, whereas already large-scale demonstrations (~60 kton/yr) are upcoming. The lack of standards for quality of this product is potentially hampering the market development and there is a need for this in short term. Also, transportation biofuels production still lack certification of the origin of the feedstock biomass and the biofuel product itself (e.g. bio-DME for transportation use), specifications of different mixtures of E10, E20, E85, B10, B20, B30....

Moreover, there is an ongoing need for subsidy programmes supporting gasifier demonstrations towards large-scale flagship projects. Implementation of demonstration plants for biofuel production based on BTL technology [Boerrigter, 2006; Biomass to Liquid, 2006]. Demonstrations based on different fuels production based on newly developed reactor concepts (within the EU, e.g. MILENA, FICFB): FTS and advanced reactors as well as bio-SNG, bio-DME, bio-methanol, bio-H_2 and possibly bio-ammonia processes. Materials needed are catalysts and gas cleanup functional materials (e.g. ceramic / metallic filters for hot gas cleaning, possibly with applied process intensification by combining separation and reaction via catalyst integration in the materials).

Basic and applied research studies towards new materials for supercritical water gasification technology to process wet biomass streams, both catalytic and construction materials are to be studied and tested.

Improved materials (alloys and coatings) which can be manufactured and joined (in-situ inside plants where needed, e.g. replacement of boiler tubes, coating stripping/replacement) and provide reliable performance are needed to handle the corrosion, erosion, slagging & fouling for up to 30% biomass thermal input in advanced coal power stations. In parallel, improved understanding of biomass combustion/gasification behaviour is required to assist in solving these problems. The impact of co-firing on plant emissions for co-firing of different biomass types and ash utilisation require further investigation. Co-firing demonstrations up to $30\%_{th}$ fuel input, with supporting R&D in parallel are required to establish co-firing as a viable approach to reducing CO_2 emissions, the value of which needs to be recognised in the EU Emissions Trading Scheme. Further development of co-firing in power stations with efficiencies approaching $50\%_{el}$ (without CCS) is needed to progress further.

4.1.B. BIO-CHEMICAL TECHNOLOGIES

Substrate pretreatment and hydrolysis technology still have potential for development and materials can play a role in abrasion and acid sensitive equipment and fermenter parts.

Utilisation of the heat from cogeneration of biogas plant units not currently utilising heat should be obligatory. The heat constitutes about 50% of the energy produced, making a doubling of the energy yield possible. Purification of the methane by new gas separation materials/technologies and on-site compression or addition to the gas grid should be facilitated. Investment costs have to be reduced by using alternative (cheap and durable) materials for plant construction.

Lignocellulosic feedstocks are generally cheap - however, treatment and hydrolysis is expensive and energy intensive. The feedstock price will rise with increased demand, which will be relieved by widening the range of feedstock able to be processed by new technology. Further, of outstanding importance for bio-ethanol production is an improvement in yield and production rate. Developments are needed in numerous fields:

- For pretreatment and hydrolysis improved sugar yields are paramount: More cost- and energy effective, feedstock-flexible pre-treatment need to be developed, as well as separation schemes where individual components of the raw material input are extracted/separated according to optimised schemes for further conversion of the individual components. Maximum recovery of the carbohydrates into fermentable sugars, high rate of conversion, and low production of fermentation inhibitors is needed.
- New, enzymes aimed at effectively breaking down the crystalline structure of the biomass cellulose must be developed, thus reducing feedstock input and residence time during hydrolysis which should thereby reduce the material needed for vessels and support equipment. Enzyme performance needs improvement by at least a factor of 2 to be economically viable.
- For fermentation an optimised use of the hemicellulose fractions is needed to get the maximum value out of the process. Genetically engineered strains, yeast and bacteria, are under research and development.

Robustness of the strains for the process or for the inhibitors and products needs to be improved. Adaptation and genetic engineering of the strains has to lead to higher productivity, product tolerance and end concentration. Substrate hydrolysis during fermentation (consolidated bioprocessing), e.g. by enzymes produced by the fermenting organisms, is a goal.

- Component separation from fermentation broth has to be improved by better materials (e.g. membranes for higher flux and better separation efficiency) and technologies for reduced energy consumption. Alternatively in situ removal of products by membrane or adsorbent technology or the like would improve process performance in yield and productivity.
- Process schemes aiming at optimised use of all process by-products (biorefinery) represents an important step forwards. New conversion routes must be developed for all process by-products, ensuring the optimal utilisation of all components of the raw material input. Economics of the process can be improved by by-product purification: CO_2, H_2, vitamins, microbial cell mass, rare solvents or carbonic acids in low amounts. Combustion or gasification of residues from substrate saccharification such as lignin increases economic value. These improvements will not change the use of construction material.
- Crucial for market implementation is the quick standardisation of new bio-fuel products such as FTS-diesel or FTS-kerosene or new products from fermentations such as i-butanol, n-butanol or mixtures of ABE.

Biogas: Subsidised prices are expected to be reduced step by step. Efficiency of plants and product quality (e.g. siloxanes, methane content) has to be improved considerably, in part by more effective feedstock pre-treatment (use of enzymes) and higher biogas yield (micro-nutrient additions). Investment cost per plant or per installed kW is expected to increase as it did in the last few years; a reduction through cheaper construction materials is needed here. Competition for dedicated crops as well as for organic waste will increase prices.

Hybrid Technologies: expected positive public opinion, petro-chemical companies wanting to green their input, environmental legislation, national government/EU subsidies; new developments in agricultural practices increasing yields of crops per ha; the technology is rather flexible so one can anticipate quickly on changing market demands.

4.2. Specification Targets for Market Implementation in 2050

According to the OECD/IEA BLUE Map scenario [OECD, 2010; IEA, 2010], biofuels, electricity and hydrogen together represent 50% of total transport fuel use in 2050, replacing gasoline and diesel. By 2050, the biomass share in final energy consumption increases globally from 10% in the Baseline scenario to 18% in the BLUE Map scenario. Other studies predict an even higher share of biomass [EcoFys, 2010; Öko-Institute, 2011]. Most of the increase in bioenergy comes from the use of biofuels in the transport sector to reduce CO_2 emissions. Biofuel use increases from 34 Mtoe in 2007 to 764 Mtoe in the BLUE Map scenario. Biofuels are particularly important to decarbonise (from fossil sources) modes of transport that lack other options (especially trucks, ships and aircraft). However, the use of biofuels for all modes will depend on the development of viable, sustainable, second-generation technologies that are not yet commercial today. Regarding the production technology the experts highlight a needed implementation of flagship plants based on BTL technology via FTS and advanced reactors.

Market implementation can be enhanced by support of bio-energy companies via tax regulations. Also, exploitation of marginal land / sea (weeds) will be needed for biomass production with less dependency on conventional land usage. A major change in the effectiveness of the world's management of agricultural and natural lands as well as forestry will be required. The challenge is that the world population will grow by 50% during the same period, with food demand rising correspondingly. To meet this demand, the total productivity of land currently in production must triple. The development and use of high-yield crops, water management, soil management and land-use policies and considerations of ecological sustainability need to be closely co-ordinated. Recent problems with rain forest and bushland clearing for first-generation biofuel crops show that a focus on energy alone can lead to undesirable outcomes.

High quality biomass and novel advanced pre-treatment technologies increase biomass addition to 50+% thermal input share in coal power stations. Co-firing demonstrations for 50+% thermal substitution of coal by biomass in coal fired stations, with CCS. Efficiency of co-fired stations increases towards 45+% with CCS, although the use of coal for heat and electricity production will decline [SRU, 2010].

Future bioenergy systems will include greater integration of process stages in order to maximise efficiency and reduce waste. With changing feedstocks over time, changing outputs requirements (e.g. increased H_2 demand,

integration of CCS, etc.) and the increasing efficiency and complexity of process stages, improved materials and protective systems will continue to be needed to allow these developments to be implemented.
Gasification is a technology that can meet the production needs of these energy carriers in a feedstock flexible way including partly fossil sources [Rensfelt, 2001].

Fermentation technologies are a complementary way of producing biofuels [Schwarz, 2007; Antoni, 2007]. Enzymatic hydrolysis of complete biomass with marginal pretreatment is possible on an economic basis by implementing new types of enzyme systems and novel pretreatment technologies which are not yet available, making a wider range of feedstock accessible. Enzyme efficiency for hydrolysis should increase by at least 25% to make enzymatic hydrolysis economically feasible. Hybrid technologies focusing on the optimal conversion of the biomass components to biofuels and value-added products are developed, in addition adding to the sustainability by making replenishment of soil components possible with process residues.

Replenishment of soil nutrients and structural material can now be widely achieved through utilisation of residues from fermentation processes and by charcoal from waste material. Fertiliser is produced from the fermentation liquids and contains sufficient macro- and micro-elements such as all phosphorous and potassium, and most of the ammonium-nitrogen from the plant material introduced to the process.

Storage of large amounts of biogas is feasible to bridge low-demand times such as long weekends where other renewable energy sources such as wind energy or photovoltaics deliver sufficient electric energy. Biogas as a reliable and easily controllable energy from small production units forms the backbone of electricity production. The grid is on one hand able to handle small producers (the majority of the producers) and on the other to control the electricity producers by temporarily shutting them down and restarting them.

The biological reutilisation of CO_2 is possible at large scale, enabling the use of sunlight in desert areas for production of storable biofuels.

The biofuels production units are feedstock flexible. According to the principles of green chemistry, the production methods switch to catalytic and enzymatic processes under mild conditions and use a minimum of energy. Production processes are selective with little residues which are useful for soil replenishment or fertilization.

Section 5. Synergies with other Technologies

5.A. Thermo-chemical Technologies

Synergies of biomass derived syngas production and its associated material developments are expected to occur in integrating the technology in petro-chemical and coal processing complexes. It also ensures diversifying energy supply. Moreover, the material development for gas cleaning can be used for other process industries (gas separation, CO_2 separation etc.), and fuel cell development. Synergies can also be realised when combining sugar production based technologies for biofuels generation (hydrolysis & fermentation) together with gasification for the residual part of biomass. Efficient utilisation of biomass via this second generation technology will contribute to improved job retention and rural area development. Exchange of technological know-how with other energy producing industries could facilitate technological progress and economies of scale (combustion, gasification equipment, gas purification and system integration). The BTL technology based on the development of advanced FTS reactors for synthetic fuel production is complementary with GTL and CTL technologies [Stiegel, 2001]. The BTL technology represents a synergy with the low temperature conversion process (transesterification process) to obtain biodiesel.

5.B. Bio-chemical Technologies

Technologies for utilisation of large amounts of lignin will have to be developed which will push science and industry a step forward to new plastics and chemicals. New technologies for biomass pretreatment and hydrolysis can be used for most other industrial fermentation sectors. Intensive research in pretreatment, hydrolysis, fermentation, heterologous production of recombinant proteins, new platform organisms for fermentation and enzyme production, downstream processing of solvents from diluted culture broth will push the development of biotechnology and bio-products in general. Development of effective separation and conversion routes for the non-fermentable biomass components (e.g. lignin, extractives)/process by-products will be critical for the development of cost-effective bio-chemical biomass processing schemes.

Development of new catalysts for conversion of fermentation products (liquid as well as gaseous) will stimulate application in other fields of biochemistry and biotechnology.

Biogas up-grading technologies allow losses of methane to varying degrees; this leads to a demand for improved up-grading technologies which will need better and lower cost materials. Turbines and fuel cell technologies need to be adapted to ensure high conversion efficiency of biogas and biomethane. Local storage of methane could be used for electricity or heat production during low electricity consumption times of the day - highly efficient (high density) methane storage technology would allow use in transportation. There can also be synergies between biogas production and supercritical water gasification as digestion leaves a wet digestate that can be used as feedstock.

5.C. Synergy with single technologies or other chapters:

Co-firing of biomass

The effects of co-firing on power plant materials of co-firing with coal are described in detail in the Bioenergy Report rather than in the Fossil Energies/CCS Report.

Bio-Carbon Dioxide Capture

Carbon dioxide capture techniques specifically for bio-CCS are not dealt with in detail in the Bioenergy Report; the Fossil Energies/CCS Report addresses CO_2 capture. CO_2 utilisation for production of enhanced biomass production (e.g. algae) is a developing field with a close interface to bioenergy processes.

Bio-Syngas for Fuel Cells

High temperature fuel cells are candidates for energy conversion of bio-syngases. Their will be materials issues that can be addressed both from the point of view of cleaning and conditioning of the bio-syngas and from the point of view of improved capability of the fuel cells to perform in the presence of contaminants.

Energy Storage

Biogas could be used for short-term storage for later use in combined heat and power (CHP) systems. The challenge is to enhance storage capacity by for example chemical/formaldehyde formation, but much research is needed.

Process Control and Monitoring

Bio-conversion processes could benefit enormously from better process control techniques that use various sensors and monitoring techniques under development in other industries. For example, biogas production rate is estimated to have potential for a factor of about 2 increase from what can now be achieved.

Biorefineries

High value products are needed to enable good economic performance of bioenergy processes. Biofuel prices are largely dictated by fossil prices and so high value chemical/material by-products are essential to the viability of energy biorefineries. Unfortunately, the lack of market development and exploitation (of resins, surfactants, etc.) is holding back biorefinery technology development. On the positive side, microbes, enzymes and catalysts are common to biorefineries and biofuel production, and both sectors can benefit from their development.

Biofuel Quality Standards

There is a need to compare the lifecycle environmental assessment of different biofuel processes and to select the most interesting solutions from the point of view of environmental impact and cost strategy to guarantee sustainability in the long term. Future development of standards for new fuels or fuel blends will be needed, since actually the standards are limited to pure fuels or some blends. The close collaboration between biofuels and engine developers are needed to guarantee the behaviour and to prevent a huge increase in the maintenance of the engine, taking into account both the engine materials (prevent corrosion and wear) and lubricant and seals compatibility.

Section 6. Needs and Recommendation of Activities addressing 2020 and 2050 Market Implementation

A general picture of technology development for some renewable energy technologies towards mass market implementation is given in OECD/IEA [2010]. All aforementioned technologies (thermo-chemical and bio-chemical routes) present different maturity levels. Technologies based on bioenergy value chains with high maturity levels should be promoted in order to achieve a large scale deployment in the near future,

- in the thermo-chemical route: e.g. synthetic liquid fuels obtained by BTL, biomethane and other gaseous fuels obtained by gasification, bioenergy carriers obtained by pyrolysis and torrefaction, and high efficiency heat and power generation obtained by thermo-chemical processes;
- in the bio-chemical route: e.g. ethanol and higher alcohols produced from ligno-cellulosic feedstock by means of biological, chemical and biochemical processes, liquid hydrocarbons through biological and/or chemical synthesis from biomass, and bioenergy carriers produced by micro-organisms, such as microalgae, or biogas (methane) from a greater variety of biomass.

Supply with more biomass within the same transportation distance or with higher energy density will allow larger plants and processes in greater scale, resulting in better economy.

All these technologies could be promoted and developed on the near term, through R&D projects devoted to the construction and operation of demonstration or flagship plants. This will depend on the available financing and executed mechanisms carried out in the latest stages of development achieved by these technologies.

6.1. Needs and Recommendations for Market Implementation in 2020/2030

6.1.A. Thermo-chemical Technologies

An important issue for market development is certification and standardisation of produced biomass derived materials otherwise there is a risk that introduction and expansion of bioenergy technologies will be hampered even at the short term. For example for torrefaction pellets, there are currently no standards at all, whereas already large-scale demonstrations (~60 kton/yr) are upcoming. The lack of standards for quality of this product is potentially hampering the market development and there is a need for this in short term. The situation is similar for bio-DME for transportation use. Co-firing is to be supported to allow higher shares of biomass (>> 10% thermal) to be combusted together with coal. Impact studies of blending on corrosion of wall and heat exchanger materials, slagging and fouling are required, as well on catalytic de-NO_x units and filtration of particulate matter cleaning.

Further integrated gasification plant demonstrations need to be supported financially utilising different technologies that have already been developed within the EU. Parallel to this demonstration action, applied accompanying research is still required in certain key areas involving catalyst materials and impact of impurities in syngas on performance. More research effort should be devoted e.g. to upstream areas of the technology chain, like feedstock production, improvements in feedstock and biomass supply logistics can contribute to overcome the problems related to the variability of physical and chemical properties of biomass feedstock. According to International Energy Agency [IEA, 2010, Base line scenario], the production levels of liquid biofuels derived from Biomass will increase significantly up to 2030. In this regard, for the period 2020–2030 it would be advantageous that demonstration plants based on small-scale and decentralised reaction systems are in operation, in order to satisfy such liquid biofuel production levels.

6.1.B. Bio-chemical Technologies

All organic residues and waste should be used for biogas formation - to reach this goal, a waste separation system should be implemented obligatory EU-wide (in Germany alone, about 10 million tons of collected biowaste are collected, but composted instead of fermented). 50% of the bioethanol and a large part of natural gas should be produced from lignocellulosic biomass and tax incentives will no longer be needed. However, subvention support by governments for implementation of flagship production plants will be needed for (combined thermo-chemical/bio-chemical) biorefineries and lignocellulosic biofuels other than ethanol and biogas. Special care should be taken to include biorefinery and Green Chemistry principles to each plant.

Legislation will have to be updated to introduce the addition of novel biofuels to gasoline, diesel and kerosene in the transportation sector.

6.2. Needs and Recommendations for Market Implementation in 2050

It was projected that depending on the scenario 11% (from 300 million toe in the reference scenario) to 80% (from 145 million toe in the vision scenario) of all transportation fuels could be biofuels in 2050 [Öko-Institute, 2011].

6.2.A. Thermo-chemical Technologies

According to the recent information of IEA [2008; BLUE Map scenario], about half of the primary bioenergy would be used for the production of liquid biofuels. The other half would be used for power generation, heating and industrial feedstocks. In this scenario the biomass would be almost tripled in comparison to its current production. This would require fundamental improvements in agriculture and forestry. The implementation of flagship plants based on small-scale and decentralised reaction systems with improved durability and efficiency must also be in operation in 2050 in order to satisfy such liquid biofuel production levels.

6.2.B. Bio-chemical Technologies

The majority of bioethanol (6 Exajoules or 120 Mtoe) is coming from cellulosic sources, with an increasing share by about 2040 [IEA, 2008]. About 600 to 700 PJ of biogas from organic waste could be produced in EU-15 by 2020. This number will not grow considerably until 2050 [INforSE and Alborg University, 2010-11-26, Kaunas].

6.3. Recommendations for Education Measures

Universities must assure (and be supported in supplying) “hands-on” state-of-the-art education and training of future engineers and research specialists in engineering, (molecular) biology, chemistry and biotechnology regarding the fate of materials in the diverse field of bioenergy conversion. Both, basic and applied science need to be strengthened for progress and success in the application and implementation of bioenergy concepts.

Specific needs (both educational and research needs):

- Fundamental knowledge of plant fiber structure and fiber chemistry. Differences between species.
- Effect of different treatments (solvents, acids, etc) on fibre structure/chemistry, fibre deconstruction
- Solubilisation of biomass components – solvents aimed at effective solubilisation
- Monitoring of process environments
- Process modeling and component life modelling
- New fermentation concepts
- Separation processes/media aimed at effective separation of biomass constituents
- Process monitoring (thermo- and bio-chemical processes)
- Enzymatic hydrolysis of plant cell wall matrices – novel enzyme systems/mixtures from a variety of biological sources, hydrolysis mechanism and synergy, role of accessory enzymes
- Bio prospecting, isolation and genetic engineering/gene transfer – development of novel microorganisms for effective conversion of biomass raw materials
- Thermo-chemical conversion of biomass/biomass constituents to bioenergy products as well as value-added products
- Novel catalysts
- Biochemistry of sugars: sugar as platform chemical
- Structural ferritic and austenitic steels, with associated manufacturing/ joining technologies and coating systems
- Process technology and engineering
- Life cycle assessment
- Corrosion and wear behaviour of advanced materials at extreme conditions

Table 2: Education necessary for optimal development of bioenergy R&D

For thermo-chemical conversion technologies:	
Materials science evaluations	Process environments and impacts on fouling, slagging and corrosion, gas engine/turbine materials, advanced heat exchangers for Stirling engines and indirect cycles, in-situ replacement technology, new alloys and protective coatings
Nano-technology	Advanced materials and process monitoring
Thermo-dynamic system	Process modelling, impacts of variable feedstock compositions, gas filtration and cleaning, biomass combustion/gasification behaviour
For Bio-chemical conversion:	
Enzymology	Enzymes in ionic liquids, enzyme action on lignocellulosic material containing cellulose, hemicellulose and lignin closely associated with each other
Molecular biology	Exploitation of biodiversity in enzyme discovery (metagenomes and genomic data), heterologous expression of enzymes, protein engineering for advanced enzymes for polymer degradation, synthetic biology
Fermentation process technology	New fermentation schemes: immobilized cells, continuous, plug flow etc., high consistency fermentation, product recovery during fermentation, online monitoring technology
For both conversion technologies:	
Reactor engineering	Development of advanced catalytic reactors, based on Process Intensification that leads to a substantially smaller, cleaner, safer and more energy efficient installation
Catalysis	Development and improvement of active, selective and stable catalysts based on affordable and plentiful precursors (active phases and catalyst carriers), scalable and uncomplicated preparation methodologies and advanced technologies (nano-technologies)
Separation process technology	Separation of gases, liquids from aggressive or from dilute solutions; in situ separation during fermentation; selective separation from product mixture (gases and liquids)
Biochemistry	For better understanding of sugar conversion – glucose/xylose as a platform chemical, conversion of fermentation products to platform chemicals
Enzyme technology	- Action of enzymes for conversion of chemicals in solvents/ionic liquids - Enzymatic hydrolysis of lignocellulosics, synergy among cellulases and with hemicellulases - Limiting factors in hydrolysis: structural inhibition, product inhibition, inhibitors from substrate - Enzyme discovery and protein engineering for second generation mixtures
Catalyst theory	For a better understanding of catalyst conversion of biomass, includes the catalytic hydrolysis of crystalline/insoluble cell wall material
Integrated studies	Understanding of complex interlinkage between technical needs, economy, ecology, planning, legislation, standardisation, and politics

Annex I: References

Adam, J.; Antonakou, E.; Lappas, A.; Stöcker, M.; Hilsen, M. H.; Bouzga, A.; Hustad, J. E.; øye, G., In situ catalytic upgrading of biomass derived fast pyrolysis vapours in a fixed bed reactor using mesoporous materials. Microporous and mesoporous materials 2006, 96, 93-101.

Antoni, D., Zverlov, V. V., Schwarz, W. H. (2007). Biofuels from microbes. Appl Microbiol Biotechnol 77:23-35.

Aravind PV, Ouweltjes JP, de Heer E, Woudstra N, Rietveld G (2005) Impact of Biosyngas and Its Components on SOFC Anodes, Electrochemical Society Proceedings, Vol 7, pp. 1459-1467.

Aravind PV, Ouweltjes JP, Woudstra N, Rietveld G (2008) Impact of biomass derived contaminants on SOFCs with Ni/GDC anodes. Electrochemical and Solid-State Letters 11: B24-B28.

Aravind, P. V.; Woudstra, T.; Woudstra, N.; Spliethoff, H., Thermodynamic evaluation of small-scale systems with biomass gasifiers, solid oxide fuel cells with Ni/GDC anodes and gas turbines. *Journal of Power Sources* **2009,** 190, (2), 461-475.

ASTM D2880, Standard Specification for Gas Turbine Fuel Oils (1990).

Balan, V., Bals, B., Chundawat, S.P.S., Marshall, D., Dale. B.E. (2009) Lignocellulosic biomass pretreatment using AFEX. 1. Ed. In: J.R. Mielenz (Ed.) Biofuels: methods and protocols. Humana Press, New York City, pp- 61-77.

Biofuels Platform (2009) Production of biofuels in the world in 2008, accessed 28 January 2010. Available at http://www.biofuelsplatform.ch/en/infos/production.php?id=biodieselBiofuels.

Biogas - an all-rounder" by Sunbeam GmbH and Fachverband Biogas e.V., 2009, or www.german-biogas-industry.com.

"Biomass to Liquid – BtL Implementation Report", Deutsche Energie-Agentur GmbH (dena) - The German Energy Agency, 2006. Available at: http://www.dena.de/fileadmin/user_upload/Download/Dokumente/Publikationen/mobilitaet/btl_implementation_report.pdf.

Biorefinery: Catalytic Conversion of Lignocellulosic Biomass using Porous Materials". Angewandte Chemie International Edition, 47 (2008) 9200.

Boerrigter H (2006) "Economy of Biomass-to-Liquids (BTL) plants: An engineering assessment", report ECN.

Bond, J.Q., Alonso, D. M., Wang, D,, West, R.M., Dumesic, J. A. (2010) Integrated Catalytic Conversion of g-Valerolactone to Liquid Alkenes for Transportation Fuels. Science 327:1110

Bridgwater A.V., 'Biomass Gasification for Power Generation', Fuel, vol. 74 no. 5 631-653 (1995).

Bridgwater, A. V., The technical and economic feasibility of biomass gasification for power generation *Fuel* **1995,** 74, (5), 631-653.

Bridgwater, A. V.; Peacocke, G. V. C., Fast pyrolysis processes for biomass. *Renewable and Sustainable Energy Reviews* **2000,** 4, 1-73.

Bridgwater, A. V. *The future for biomass pyrolysis and gasification: status, opportunities and policies for Europe*; Bio-Energy Research Group, Aston University: Birmingham (UK), 2002.

Bridgwater, A. V., Renewable fuels and chemicals by thermal processing of biomass. *Chemical Engineering Journal* **2003,** 19, (2-3), 87-102.

Cardona, C.A., Sanchez, O.J. (2007) Fuel ethanol production: Process design trends and integration opportunities, Bioresource Technology, Volume 98, Issue 12, Pages 2415-2457.

Chinchen, G. C.; Denny, P. J.; Jennings, J. R.; Spencer, M. S.; Waugh, K. C., Synthesis of methanol. *Applied Catalysis* **1988,** 36, 1-65.

'Co-gasification of Coal/Biomass and Coal/Waste Mixtures', Final Report EC APAS Contract COAL-CT92-0001, University of Stuttgart, Germany (1995).

Dai, J.; Sokhansanj, S.; Grace, J. R.; Bi, X.; Lim, C. J., Overview and some issues related to co-firing biomass and coal. *The Canadian Journal of Chemical Engineering* **2008,** 86, 367-386.

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

Dry, M.E.: "The Fischer-Tropsch process: 1950–2000". Cat. Today 71 (2002) 227–241.

EcoFys (2010) The energy report. 100% renewable energy by 2050. http://www.ecofys.com/com/publications/The-Energy-Report-Ecofys.htm on March 11, 2011.

ECSC Project 7220-PR/053, `Gas turbines in advanced co-fired energy systems' .

EPA – U.S. Environmental Protection Agency: http://www.epa.gov/gcc/pubs/principles.html (March 8th, 2011)

GEVO Inc., http://www.gevo.com/ (on March 7th 2011)

Grabke HJ (2002) “Carburization, Carbide Formation, Metal Dusting, Coking”. Materiali in Tehnologije, 36(6): 297–305.

Grimes, C. A., Varghese, O.K., Ranjan, S. (2008) Light, Water, Hydrogen – The Solar Generation of Hydrogen by Water Photoelectrolysis, Springer, ISBN 978-0-387-33198-0.

Gupta, R. B., *Hydrogen Fuel: Production, Transport and Storage*. CRC press: Boca Raton (Florida, USA), 2009.

Hamelinck CN (2004) Outlook for Advanced BiofuelsDepartment of Science, Technology and Society University of Utrecht, Utrecht.

Higman C., M. van der Burgt (2003) Gasification, Elsevier Science, Burlington, ISBN 0-7506-7707-4.

‘Hot Corrosion Standards, Test Procedures and Performance’, High Temperature Technology vol. 7 (4) (1989).

Horváth, I.T., Mehdi, H., Fábos, V., Boda, L., Mika, L.T. (2008) γ-Valerolactone—a sustainable liquid for energy and carbon-based chemicals. Green Chem., 10:238-242

Hsu, T. (1996) in: C.E. Wyman (Ed.) Handbook on bioethanol: production and utilization. Taylor & Francis, Washington, DC, pp. 179-212.

Huber, G. W., Chheda, J.N., Barrett, C. J., Dumesic, J. A. (2005); Production of Liquid Alkanes by Aqueous-Phase Processing of Biomass-Derived Carbohydrates. Science 308:1446

IEA 2010, “Energy Technology Perspectives: Scenarios & Strategies to 2050”, Available at http://www.ies.org/Textbase/about/copyright.asp

IEA task 42 “Biorefineries” has made the following definition: ”The sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, and/or materials) and bioenergy (biofuels, power and/or heat)”.

Jacobsen, H. 2010. ‘Heterogreeneous Chemistry’. Handbook of Green Chemistry. 93–116.

Jörß, Wolfram et al. (2003) Decentralised Power Generation in the Liberalised EU Energy Markets, Springler-Verlag, Berlin, ISBN 3-540-40133-4.

De Jong W (2008) Sustainable Hydrogen Production by Thermochemical Biomass Processing. In: Gupta RB (ed) Hydrogen Fuel: Production, Transport and Storage CRC Press (Taylor & Francis), Boca Raton (USA, Florida), pp. 185-22.

Kamm, B.; Gruber, P. R.; Kamm, M., *Biorefineries - Industrial Processes and Products; Status Quo and Future Directions*. Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, 2006.

Khan, A. A.; De Jong, W.; Jansens, P. J.; Spliethoff, H., Biomass combustion in fluidized bed boilers: Potential problems and remedies. *Fuel Processing Technology* **2009,** 90, 21-50.

Kim, S., Holtzapple, M.T. (2005a) Lime pretreatment and enzymatic hydrolysis of corn stover. Biores. Technol. 96: 1994-2006.

Kim, T.H., Lee, Y.Y. (2005b) Pretreatment and fractionation of corn stover by ammonia recycle percolation process. Biores. Technol. 96: 2007-2013.

Knoef H (2005) Handbook Biomass Gasification BTG biomass technology group, Enschede

Kopyscinski, J.; Schildhauer, T. J.; Biollaz, S. M. A., Production of synthetic natural gas (SNG) from coal and dry biomass – A technology review from 1950 to 2009. *Fuel* **2010,** 89, 1763-1783.

Kritzer P (2004) Corrosion in high-temperature and supercritical water and aqueous solutions: a review. Journal of Supercritical Fluids 29: 1-29.S.

Kumar, S. P. Singh, I. M. Mishra, D. K. Adhikari (2009) Recent Advances in Production of Bioethanol from Lignocellulosic Biomass, Chemical Engineering & Technology, Volume 32, Issue 4, pages 517-526.

Lange,J.P., Price, R., Ayoub, P.M., Louis, J., Petrus, L., Clarke, L., Gosselink, H. (2010) Valeric Biofuels: A Platform of Cellulosic Transportation Fuels. Angew. Chem. 122:4581 –4585

Liu, C., Wyman, C.E. (2005) Partial flow of compressed-hot water through corn stover to enhance hemicelluloses sugar recovery and enzymatic digestibility of cellulose. Biores. Technol. 96: 1978-1977.

Lloyd, T.A., Wyman, C.E. (2005) Combined sugar yields for dilute sulphuric acid pretreatment of corn stover followed by enzymatic hydrolysis of the remaining solids. Biores. Technol. 96: 1967-1977.

Matsumura, Y.; Minowa, T.; Potic, B.; Kersten, S. R. A.; Prins, W.; Van Swaaij, W. P. M.; Van de Beld, B.; Elliott, D. C.; Neuenschwander, G. G.; Kruse, A.; Antal, M. J., Biomass gasification in near- and super-critical water: Status and prospects. *Biomass & Bioenergy* **2005,** 29, 269-292.

Matsumura Y, Minowa T, Potic B, Kersten SRA, Prins W, Van Swaaij WPM, Van de Beld B, Elliott DC, Mc Phail SJ, Aarva A, Devianto H, Bove R, Moreno A (2010) SOFC and MCFC: Commonalities and opportunities for integrated research. International Journal of Hydrogen Energy article in press.

Meng, X.; de Jong, W.; Verkooijen, A. H. M., In bed and downstream hot gas desulphurization during solid fuel gasification: A review. *Fuel Processing Technology* **2010,** 91, (8), 964-981.

Mosier, N., Wyman, C, Dale, B., Elander, R., Lee, Y.Y., Holtzapple, M., Ladisch, M. (2005) Features of promising technologies for pretreatment of lignocellulosic biomass. Biores. Technol. 96: 673-686.

Müller-Langer, F., Perimenis, A., Brauer, S., Thrän, D., Kaltschmitt, M. (2008) ‚Technische und ökonomische Bewertung von Bioenergie-Konversionspfaden‘, Berlin WBGU.

Neuenschwander GG, Kruse A, Antal MJ (2005) Biomass gasification in near- and super-critical water: Status and prospects. Biomass & Bioenergy 29: 269-292.

Ni, Y., Sun, Z. (2009) Recent progress on industrial fermentative production of acetone-butanol-ethanol by *Clostridium acetobutylicum* in China. Appl. Microbiol. Biotechnol. 83:415-423.

Nishiyama Y, Otsuka N, Kudo T (2006) ”Metal dusting behaviour of Cr-Ni steels and Ni-base alloys in a simulated syngas mixture”. Corrosion Science 48: 2064–2083.

Oakey JE, Simms NJ and Kilgallon PJ, ‘Gas Turbines: Gas Cleaning Requirementsfor Biomass-fired Systems’, Materials Research: (Revista Ibero-Americana De Materials), 7 (1) (2004)

Oakey JE and Bagley CJ, Materials UK, Strategic Research Agenda – Alternative Energy Technologies (2007)

OECD/IEA (2010) Energy Technology Perspectives - Scenarios and Strategies to 2050 International Energy Agency, Paris (France).

Ohara, H. (2003) Biorefinery, Applied Microbiological Biotechnology, 62:474–477

Öko-Institut (2011) The Vision Scenario for the European Union. 2011 Update for the EU-27. www.oeko.de

Palmqvist, E., Hahn-Hägerdahl, B., Galbe, M., Zacchi, G. (1996) The effect of water-soluble inhibitors from steam-pretreated willow on enzymatic hydrolysis and ethanol fermentation. Enz. Microb. Technol. 19:470-476.

Palmqvist, E., Hahn-Hägerdahl, B. (2000) Fermentation of lignocellulosic hydrolysates. II: inhibitors and mechanisms of inhibition.

Biores. Technol. 74: 25-33.

Phair, J.W., Badwal, S.P.S. (2006) Materials for separation membranes in hydrogen and oxygen production and future power generation, Science and Technology of Advanced Materials, Volume 7, Number 8.

Pinatti DG, Conte RA, Soares AG, Pereira MLG, Romão EL, Ferreira JC, Oliveira I, Marton LFM (2010) “Biomass Refinery as a Renewable Complement to Petroleum Refinery”. Int. J. Chem. React. Eng., 8: paper A94.

Prins, M. J.; Ptasinski, K. J.; Janssen, F. J. J. G., More efficient biomass gasification via torrefaction. *Energy* **2006,** 31, 3458-3470.

Reay D (2008) “The roles of Process Intensification in Cutting Greenhouse gas emissions”. Appl. Therm, Eng. 28: 2011–2019.

Rensfelt, E., ‘Gasification Technology for Biomass and Other Solid Fuels’, Biosolids Energy Recovery Technology Seminar, IWEX 2001, Birmingham UK, (Oct 2001).

RFCS: Synopsis of the coal & steel projects co-financed by the RFCS 2007-2010 , EC (2010).

Richard T, Poirier J (2010) Selection of Ceramics and Composites as Materials for a Supercritical Water Gasification (SCWG) Reactor. Advances in Science and Technology 72: 129-134.

Rohde MP, Unruh D, Schaub G (2005) “Membrane application in Fischer-Tropsch synthesis reactors– Overview of concepts”.Cat. Today 106: 143–148

Rostrup-Nielsen, J. R., Fuels and energy for the future: the role of catalysis. *Catalysis Reviews - Science and Engineering* **2004,** 46, (3), 247-270.

Roussos, S., Soccol, C.R., Pandey, A., Augur, C. [Ed.] (2003) New Horizons in Biotechnology, Kluwer Academic Publishers, Dordrecht, ISBN 1-4020-1718-9.

Schwarz, W.H., Slattery, M., & Gapes, J.R. (2007) The ABC of ABE. BioWorld Europe 02-2007, 8-10.

Sharma, S. D.; Dolan, M.; Ilyushechkin, A.; McLennan, K.; Nguyen, T.; Chase, D., Recent developments in dry hot syngas cleaning processes. *Fuel* **2010,** 89, 817-826.

Shearing PR, Brett DJL, Brandon NP (2010) Towards intelligent engineering of SOFC electrodes: a review of advanced microstructural characterisation techniques. International materials reviews 55: 347-363.

Sims C.T., N. S. Stoloff and W.C. Hagel, ‘Superalloys II’, Wiley (1987).

Simms NJ, Kilgallon PJ and Oakey JE, ‘Fireside Issues in Advanced Power Generation Systems’, PARSONS 2007, Power Generation in an Era of Climate Change, Proc. of the Seventh International Charles Parsons Conference, 11 – 13 September 2007, ISBN1-86125-168-8

Sjaak van Loo, Jaap Koppejan [Ed.] (2008) The handbook of biomass combustion an co-firing, London, Earthscan, ISBN 978-1-84407-249-I

Spliethoff, H., *Power generation from solid fuels*. Springer Verlag: Berlin-Heidelberg, 2009.

SRU (2010), Wege zur 100 % erneuerbaren Stromversorgung, http://www.umweltrat.de/cln_137/SharedDocs/Downloads/DE/02_Sondergutachten/2011_Sondergutachten_100Prozent_Erneuerbare.html.

Stahl K. and M. Neergaard, ‘IGCC Power Plant for Biomass Utilisation, Varnamo, Sweden’, Biomass and Bioenergy, vol. 15, no. 3 (1998).

Stiegel GJ, Clayton SJ (2001) “Gasification Technologies: A Program to Deliver Clean, Secure and Affordable Energy”, National Energy Technology Laboratory, USA. [http://www.ntis.gov/search/product.aspx?ABBR=PB2010101820]

Stöcker M. (2008),. „Biofuels and Biomass-To-Liquid Fuels in the Biorefinery: Catalytic Conversion of Lignocellulosic Biomass using Porous Materials” Angewandte Chemie Internat. Ed., **47** (2008) 9200.

Subramanian, G. [Ed.] (2007) Bioseparation and Bioprocessing, WILEY-VCH Verlag GmbH & Co. KgaA, Weinheim. ISBN 978-3-527-31585-7.

Sutton, D.; Kelleher, B.; Ross, J. R. H., Review of literature on catalysts for biomass gasification. *Fuel Processing Technology* **2001,** 73, (3), 155-173.

Svoboda, K.; Pohorely, M.; Hartman, M.; Martinec, J., Pretreatment and feeding of biomass for pressurized entrained flow gasification. *Fuel Processing Technology* **2009,** 90, 629-635.

Talebnia, F., Karakashev, D., Angelidaki, I. (2010) Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation, Bioresource Technology, Volume 101, Issue 13, Pages 4744-4753.

Teymouri, F., Laureano-Perez, L., Alizadeh, H., Dale, B.E. (2005) Optimization of the ammonia fiber explosion (AFEX) treatment parameters for enzymatic hydrolysis of corn stover. Biores. Technol. 96: 2014-2018.

Tonovich AL, Mazanec T, Jarosch K, Fitzgerald S, Yang B, Taha R, Kilanowski D, Lerou J, MacDaniel J, Dritz T (2008) “Improved Fischer-Tropsch Economics Enabled by Microchannel Tecnology”. Velocys ©, 1–7. Available at http://www.velocys.com.

van Zyl WH, Lynd LR, den Haan R, McBride JE (2007). Consolidated *bioprocessing for bioethanol production using Saccharomyces cerevisiae*. Adv Biochem Eng Biotechnol. 2007;108:205-35

Werpy T, Petersen G, Aden A, Bozell JJ, Holladay J, White J, Manheim A, Elliot D, Lasure L, Jones S, Gerber M, Ibsen K, Lumberg L, Kelly S (2004) Top Value Added Chemicals from Biomass, Volume 1 - Results of Screening for Potential Candidates from Sugars and Synthesis Gas (NREL/TP-510-355532) US Department of Energy.

Wyman, C.E., Dale, B.E., Elander, R.T., Holtzapple, M., Ladisch, M.R., Lee, Y.Y. (2005) Coordinated development of leading biomass pretreatment technologies. Biores. Technol. 96: 1959-1966.

Yang, B., Wyman, C, E. (2008) Pretreatment: the key to unlocking low-cost cellulosic ethanol, Biofuels, Bioproducts and Biorefining, Volume 2, Issue 1.

Zhang X, Chan SH, Li G, Ho HK, Li J, Feng Z (2010) A review of integration strategies for solid oxide fuel cells. Journal of Power Sources 195: 685-702.

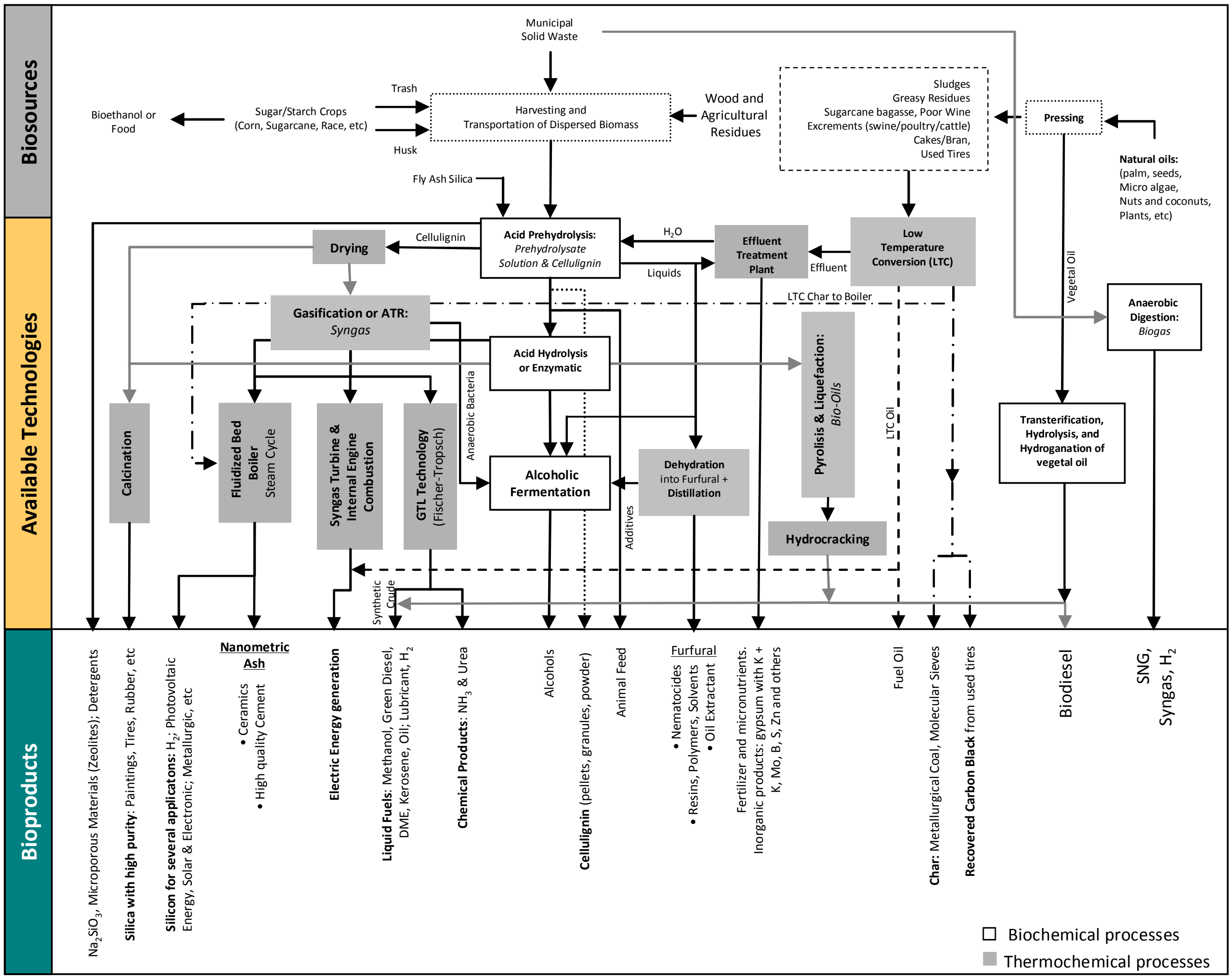
Zverlov, V. V., Berezina, O., Velikodvorskaya, G. A., & Schwarz, W. H. (2006) Bacterial acetone and butanol production by industrial fermentation in the Soviet Union: use of hydrolyzed agricultural waste for biorefinery. Appl. Microbiol. Biotechnol. 71: 587-597.

Annex II
List of Abbreviations

ABE fermentation	Acetone-butanol-ethanol fermentation (with clostridia)
BR	Biorefinery
BTL	Biomass to Liquid(s)
CCS	Carbon Capture and Storage
CHP	Combined heat and power
ESP	Electrostatic Particulate matter removal
FTS	Fischer-Tropsch synthesis
GTL	Gas to Liquid(s)
MCFC	Molten Carbonate Fuel Cell
MSCR	Micro-structured catalytic reactors
R&D	Research and Development
SCR	Selective Catalytic Reduction (a DeNOx strategy)
SMR	Small Modular Reactor
SNG	Substitute (or synthetic) Natural Gas
SOFC	Solid Oxide Fuel Cell
SSF	Simultaneous saccharification and fermentation

Annex III:

Fig. 1: Technologies for Biomass utilisation – substrates and products. This table shows the complexity of biomass utilisation in a schematised biorefinery concept.


Biosources
Available Technologies
Bioproducts
Municipal Solid Waste
Trash
Husk
Bioethanol or Food
Sugar/Starch Crops (Corn, Sugarcane, Race, etc)
Harvesting and Transportation of Dispersed Biomass
Wood and Agricultural Residues
Sludges
Greasy Residues
Sugarcane bagasse, Poor Wine
Excrements (swine/poultry/cattle)
Cakes/Bran,
Used Tires
Pressing
Natural oils: (palm, seeds, Micro algae, Nuts and coconuts, Plants, etc)
Fly Ash Silica
Acid Prehydrolysis: Prehydrolysate Solution & Cellulignin
Cellulignin
Drying
H_2O
Effluent Treatment Plant
Low Temperature Conversion (LTC)
Effluent
Liquids
LTC Char to Boiler
Vegetal Oil
Anaerobic Digestion: Biogas
Gasification or ATR: Syngas
Acid Hydrolysis or Enzymatic
Pyrolisis & Liquefaction: Bio-Oils
Anaerobic Bacteria
LTC Oil
Transterification, Hydrolysis, and Hydroganation of vegetal oil
Calcination
Fluidized Bed Boiler Steam Cycle
Syngas Turbine & Internal Engine Combustion
GTL Technology (Fischer-Tropsch)
Alcoholic Fermentation
Dehydration into Furfural + Distillation
Additives
Hydrocracking
Synthetic Crude
Na_2SiO_3, Microporous Materials (Zeolites); Detergents
Silica with high purity: Paintings, Tires, Rubber, etc
Silicon for several applicatons: H_2; Photovoltaic Energy, Solar & Electronic; Metallurgic, etc
Nanometric Ash
• Ceramics
• High quality Cement
Electric Energy generation
Liquid Fuels: Methanol, Green Diesel, DME, Kerosene, Oil; Lubricant, H_2
Chemical Products: NH_3 & Urea
Alcohols
Cellulignin (pellets, granules, powder)
Animal Feed
Furfural
• Nematocides
• Resins, Polymers, Solvents
• Oil Extractant
Fertilizer and micronutrients.
Inorganic products: gypsum with K + K, Mo, B, S, Zn and others
Fuel Oil
Char: Metallurgical Coal, Molecular Sieves
Recovered Carbon Black from used tires
Biodiesel
SNG, Syngas, H_2
☐ Biochemical processes
▨ Thermochemical processes

Annex III Table 1: Structural Materials Priorities

Technology priority areas	Technical Challenge	Key applied R&D needs	Key fundamental R&D needs	Key supporting R&D needs
1. Reducing Time to Market, Life Cycle Environmental Impact	• Improved understanding of corrosion mechanisms and development of resistant alloys and protective coatings for boilers, gas turbines and combustion engines. • Improved reactor designs and fabrication.	• Improved materials selection and plant design approaches to minimise risk of damage, materials/fabrication costs and facilitate service/repair.	• Generation of design-relevant materials data for alloys, coatings and joints. • Definition of plant operating limits for different biomass types. • Assessment of fuel additives and operational options to reduce fouling/corrosion.	• Networking with other biomass plant operators –shared experience to reduce risks. • Data generation for different biomass fuels/operating conditions for model development. • Lifecycle cost and environmental impact of different biofuels generation processes and use phase. • Collaboration on novel diagnostic techniques.
2. Higher performance in Harsher Environments	• Excessive corrosion limiting steam temperatures in boilers and syngas coolers and hot corrosion in gas turbines and combustion engines. • Advanced materials for process reactors, e.g. FT • Reduced heat loss in distributed heat systems • Refractory life limited by process environments • Fermentation containment and seal materials • Wear of biomass harvesting and process equipment	• Development of reliable alloy/coating materials systems. Improved understanding of the effects of operating conditions on corrosion rates leading to improved designs. • Improved additives or process changes to reduce the risks of excessive corrosion • Improved insulation materials • Refractories with increased resistance to chemical attack • Improved wear resistant materials and coatings • Improved wear resistance and chemical compatibility of seal materials	• Development of advanced smart coatings to resist variable corrosion mechanisms. • Determination of alloy/coating performance limits. • Improved understanding of process environments. • Development of less harsh process parameters	
3. Improved Life management and reliability	Reductions in operating and maintenance (O&M) costs	• Development and application of diagnostic techniques and process design. Improved repair procedures • Compatibility of biofuels with materials and lubricants for safe application in engines	• Characterisation of alloy/coating degradation mechanisms • Development of predictive models relating fuel properties and operating conditions to damage	

Annex III Table2: Functional and Process Materials Priorities

Technology priority areas	Technical Challenge	Key applied R&D needs	Key fundamental R&D needs	Key supporting R&D needs
Improved performance of reactors and process systems	• Low cost oxygen production • High efficiency separation of gas and liquid products and contaminants • Improved catalysts and sorbents for process and gas cleaning applications • Effective new process design	• Improved oxygen separation membranes • Process gas separation membranes – hydrogen, etc • Durable gas filtration media – ceramics/metals/intermetallics/polymers • Durable, agglomeration resistant bed materials for FB gasifiers • De-NOx catalysts for bioenergy flue gases • Oxygen carriers for chemical looping systems • S removal sorbents for catalyst protection and fuel cell applications • Ammonia reduction catalysts for biogas • Hydrotreating catalysts for bio-oil upgrading • Sorbents for biogas purification • Improved separation membranes for fermentation products, improved flux and selectivity • Improved membranes for liquid product upgrading, e.g. pervaporation, dehyrdation, etc	• Improved understanding of interactions between fluids and separation media • Better understanding of the mechanisms of catalysts poisoning and deposition of contaminants • Recycling methods for catalysts and enzymes • Continuous fermentation processes	• Improved models of process performance • Models for process costs and environmental assessment • Data generation for different biomass fuels/operating conditions for model development. • Networking with other biomass plant operators – shared experience to reduce risks. • Standardization of primising biofuels and their blends
Disposal and utilisation of residues	• Improved utilisation or reduced disposal costs for process residues and ashes	• Development of minerals recovery methods for biomass-derived residues	• Recovery methods for minor and major minerals	
Improved Life management and reliability	• Reductions in operating and maintenance (O&M) costs	• Improved process sensors for monitoring products and contaminants • Sensors for materials performance	• Improved understanding of process parameters	

Annex III Table 3: Selected Research Project Funding Supporting Bioenergy Related Fields

Research Projects				
Country /EU	**Name/Title**	**Website/ source**	**Framework and Time line**	**Targets**
				COMBUSTION & CO-FIRING
EU	**AUSPLUS**	[RFCS]	RFCS,≤2014	Combustion and co-firing, focus at steels
EU	**BIOASH**	-	FP6,<2007	Combustion and co-firing, fate of ash/aerosols
EU	**DEBCO**	www.debco.eu	FP7,≤2012	Combustion and co-firing: Demonstration of large scale Biomass CO-firing and supply chain integration
EU	**DOMOHEAT**	http://www.escansa.com/domoheat/	FP6,≤2011	Combustion (co-firing), agricultural residue based heating systems (small-scale)
EU	**ENERCORN**	http://www.acciona-energia.com/innovation/biomass/enercorn-project.aspx?pag=&desde=1992	FP7	Combustion and co-firing: Demonstration of an energy efficient corn stover biomass power plant
EU	**FLEXGAS**	www.flexgas.cnr.it	RFCS,≤2010	Combustion and co-firing: overcoming the potential disadvantages of fluidised bed gasification by co-processing biomass/waste together with coal
EU	**LAHTISTREAMS**	www.lahtistreams.com	FP6,≤2011	Waste utilization via gasification, co-firing in boiler
EU	**NEXTGENBIOWASTE**	http://www.nextgenbiowaste.com/	FP6,≤2010	Waste and biomass combustion, ash utilization
EU	**NEXTGENPOWER**	https://projects.kema.com/sites/NEXTGENPOWER	FP7,<2014	Meeting the materials and manufacturing challenges for ultra-high-efficiency PF power plants with CCS
EU	**OLIVEPOWER**	-	FP6,≤2011	Combustion of olive residues
EU	**SMARTBURN**	[RFCS]	RFCS,≤2011	Combustion and co-firing
EU	**CLEANENGINE**	http://www.crfproject-eu.org/ProgettiCRF/Sito/sites/CLEANENGINE/top.htm	FP6, <2010	Clean combustion of biofuels in engines
				PYROLYSIS & GASIFICATION
EU	**AER-II**	www.aer-gas.de	FP6,≤2008	Gasification towards high H_2 yields using sorbent materials
EU	**BioPRO**	www.eu-projects.de	FP6,≤2008	Gasification, novel clean burner development
EU	**BIOCOUP**	www.biocoup.com	FP6,≤2011	Pyrolysis of biomass for integration in biorefineries
EU	**BioDME**	www.biodme.eu	FP7,≤2012	Gasification of black liquor from paper & pulp industry towards DME from syngas

EU	**Biocellus**	www.biocellus.com	FP6,≤2007	Gasification; impact of minor contaminants in the syngas on fuel cell
EU	**Biofucel**	http://www.ien.com.pl/pl/zpc_a/zpc_prace6.php	Marie Curie	Gasification; impact of minor contaminants in the syngas on fuel cell
EU	**BioLiquids CHP**	http://www.bioliquids-chp.eu/	FP7,≤2012	Pyrolysis and CHP
EU	**BIO-SNG**		FP6≤2009	SNG production based on biomass gasification
	BioTFuel			Gasification/gas cleaning
EU	**CHRISGAS**	http://lnu.se/research-groups/chrisgas;jsessionid=6F3584ECF70866425B1284D2AF2822F1?l=en	FP6,≤2010	Clean hydrogen-rich syngas generation from biomass via gasification; gas cleaning & upgrading
EU	**ENERCOM**	**-**	FP7,≤2011	Among other techniques, gasification
EU	**GreenFuelCell**	**-**	FP6,≤2007	Gasification; impact of minor contaminants in the syngas on fuel cell
EU	**Greensyngas**	www.eat.lth.se/greensyngas/	FP7,≤2011	Biofuel production: environmentally optimised synthetic biofuel
EU	**OPTFUEL**	www.optfuel.eu	FP7,≤2012	BtL diesel production from biomass
EU	**PILLS**			Gasification/gas cleaning
EU	**RENEW**	www.renew-fuel.com	FP6,<2009	Biofuel production via gasification, gas cleaning & upgrading
EU	**SUPER METHANOL**	www.supermethanol.eu	FP7,≤2012	Supercritical water gasification technology development, glycerine processing
EU	**UNIQUE**	www.uniqueproject.eu/	FP7,≤2011	Hot gas cleaning of syngas for advanced CHP (e.g. fuel cells)
				BIO-CHEMICAL CONVERSION
EU	**BABETHANOL**	www.babethanol.com	FP7,≤2013	Second generation bio-ethanol production
EU	**BIOWALK4BIOFUELS**	http://www.biowalk4biofuels.eu/	FP7,≤2014	Biogas production from algae
EU	**CANEBIOFUEL**	www.canebiofuel.org	FP7,≤2011	Second generation bio-ethanol production from bagasse
EU	**CROPGEN**	http://www.cropgen.soton.ac.uk/	FP6,≤2007	Biogas production
EU	**FLEXFUEL**	**-**	FP6,≤2007	Biogas and ethanol production
EU	**HYVOLUTION**	http://www.biohydrogen.nl/hyvolution	FP6,≤2010	Biological hydrogen production
EU	**HYPE**	http://www.inbicon.com/Projects/HYPE/Pages/HYPE.aspx	FP7,≤2012	Ligno-cellulosic ethanol production, enzyme development, cost reduction
EU	**NILE**	http://www.nile-bioethanol.org/	FP6,≤2009	New Improvements for Ligno-cellulosic Ethanol
EU	**PLANTPOWER**	www.plantpower.eu	FP7,≤2013	Biological hydrogen production, integration in fuel cells
EU	**SOLARH2**	-	FP7,≤2011	Hydrogen production via photo-biotechnologies and biomimetic approach
EU	**VALORGAS**	http://www.valorgas.soton.ac.uk/	FP7,≤2013	Anaerobic Digestion, Bio-chemical conversion of food derived biomass

EU	**EU-DISCO**	www.disco-project.eu	2008-2012	Discovery of novel enzymes and elucidation of hydrolysis mechanisms
				BIOREFINERIES
EU	**AFORE**	http://www.eu-afore.fi/	NMP,≤2013	novel, industrially adaptable and techno-economically viable bio-based solutions for the separation, fractionation, and primary upgrading of green chemicals
EU	**BIOCORE**	www.biocore-europe.org/	FP7,≤2014	Ligno-cellulosic biorefinery development based on bio-chemical conversion and catalytic pyrolysis
EU	**BIOREF-INTEG**	http://www.bioref-integ.eu/home/	FP7,≤2010	Biorefinery technology development
EU	**BIOSYNERGY**		FP6,≤2011	Fractionation of biomass; development of biorefinery technology
EU	**DIBANET**	http://dibanet.org	FP7,≤2012	Biorefinery technology development for novel biodiesel (levulinic acid/ethanol)
EU	**EuroBioRef**	www.eurobioref.org	FP7,≤2014	Biorefinery development
EU	**GLYFINERY**	-	FP7,≤2012	Biorefinery development based on glycerol, biocatalysis
EU	**PROPANENERGY**	-	FP7,≤2011	Biogas production, propanediol and fertilizer in biorefinery approach
				NATIONAL PROGRAMMES
D	**BioEnergie 2021 (BMBF)**	http://www.bmbf.de/de/12075.php?TF=1#map	**<2012**	Broad spectrum of bioindustry related R&D within the "Hightech Strategy 2020"
D	**BioÖkonomie 2030 (BMBF)**	http://www.bmbf.de/pub/biooekonomie_kurzfassung.pdf	**<2012**	National Research Strategy for Bio-Economy (Federal Ministry of Education and Research)
D	**"Nachwachsende Rohstoffe" (FNR)** (renewable resources)	http://www.fnr-server.de/cms35/index.php?id=139		Spectrum of programs for sustainable used of renewable sources (FNR, BMELV - German Federal Ministry of Food, Agriculture and Consumer Protection)
DK	**bornbiofuel**			
DK	**KACELLE**	www.inbicon.com		the Kalundborg Cellulosic Ethanol Project
F	**BIOTFUEL**		<2013	Torrefaction, gasification, FT diesel production
NL	**ADEM**	http://www.adem-innovationlab.nl/	<2014	Large programme targeted at advanced material development for energy conversion systems (incl. bioenergy)
NL	**BE-BASIC**	www.be-basic.org	<2014	Biorefinery technology development via bio-chemical routes
NL	**EOS programme**	www.agentschapnl.nl	<2013	Large programme on energy research with projects on co-firing, gasification for CHP and biofuels, biorefinery technology development
NO	**CenBio**	**www.cenbio.no**	<2017	National research center for environmental friendly energy with focus on bioenergy. Biomass production, harvesting and transportation, their conversion to heat, power and biogas, and the handling and upgrade of residues to valuable products.
NO	**GasBio**	**http://www.sintef.no/Projectweb/GasBio/**	<2014	Biofuels production via biomass Gasification

NO	**KRAV**	**http://www.sintef.no/Projectweb/krav**	<2011	Small-scale CHP
NO	**LignoRef**	**?**		Lignocellulosics as a basis for second generation biofuels and the future biorefinery
NO	**StableWood**	**http://www.sintef.no/Projectweb/Stablewood**	<2014	Domestic heating – heating of residences with low heat demand. heat distribution within a residence with point heating.
UK	**ASPECT (TSB Project)**		<2012	Advanced surface protection to enable carbon abatement technologies – boiler fireside and steam-side coatings for co-firing and oxy-combustion
UK	**Corrosion modelling (TSB Project)**		2007-2011	Life prediction modelling in advanced boiler environments – co-firing and oxy-combustion
UK	**EPSRC Supergen Bioenergy**	**www.supergen-bioenergy.net**	2003-2011	Biomass production, energy conversion (pyrolysis/gasification), materials issues
UK	**EPSRC Supergen – Plant Life Extension**		2004-2012	Life extension issues in conventional power plants, including co-firing and gas turbine materials
UK	**SURF**		2010-	Sustainable Use of Renewable Fuels
UK	**ERDF sponsored project – OASIS**		2010-	Offshore Algae Supply Infrastructures

ANNEX III Table 4: Selected Actors in the Field of Bioenergy

Actors		
Country	**Name**	**Relevant fields of activity**
http://www.biofuelsdigest.com/	List of 50 producers of biofuels	Biofuels
A	Desmet Ballestra	Bioprocess engineering, process technology
A	Entec Biogas GmbH	Biogas plant engineering
A	Repotec/Vienna University/Bioenergy2020+	Biomass gasification for CHP / SNG via FICFB technology
A	Vogelbusch	Bioprocess engineering, process technology
BE	Cargill, bioro	Biodiesel, biorefinery development
BE	TFC	Production of furfuryl alcohol & resins based on furfural from biomass
CH	Zorg Biogas AG	Biogas plant construction and operation
D	Bayerische Landesanstalt für Landwirtschaft (LfL), Landtechnik	Biogas research and development
D	Binowa Umweltverfahrenstechnik GmbH	Biogas plant engineering
D	Bioliq (KIT)	2nd generation biofuels
D	BioRefinery 2021	Energy from Biomass, Cluster
D	Biowert Industrie GmbH	Carbon utilization and energy production from grass
D	B.T.S. Biogas GmbH	Biogas plant engineering
D	Cognis GmbH	Special chemicals from biomass
D	Choren	Syngas production, biomass gasification, Fischer-Tropsch-Synthesis
D	CropEnergies AG	
D	DaimlerCrysler AG	Support of biofuels production for car implementation
D	Dyckhoff – Biogasanlagen	Biogas plant engineering
D	E.U.R.O. Biogas Anlagenbau GmbH	Biogas plant engineering
D	European Bioplastics e. V.	Coordination of relevant companies active in bioplastic production
D	Direvo	Enzyme development for fuel production
D	Fachverband Biogas e.V. (Freising)	Biogas monitoring (http://www.biogas.org)
D	Gutachter Gemeinschaft Biogas GmbH	Biogas plant monitoring and counceling
D	Hörmann-RAWEMA GmbH	Bioenergy plant construction & engineering
D	ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH	Eco-bilancing of biorefineries
D	InfraLeuna GmbH; CBP, Fraunhofer-Zentrum für Chemisch Biotechnologische Prozesse	Lignocellulose Biorefinery pilot plant
D	Karlsruher Institut für Technologie (KIT)	Lignocellulose Biorefinery
D	KWS Saat AG	Breeding for energy plants
D	Leibniz-Institut für Agrartechnik Potsdam-Bornim e. V.	Pilot plant for Biotechnology
D	Linde KCA	Plant engineering, process technology
D	Lurgi	Plant engineering

D	nova-Institut GmbH	Biorefinery
D	Pall Filtersystems	High temperature ceramic filters for syngas
D	Schmack Biogas GmbH (Viessmann Group)	Biogas plant engineering, monitoring, surveillance
D	Uhde	Plant engineering, process technology
D	Volkswagen AG	Support of biofuels production for car implementation
DK	Babcock Wilcox Volund	Updraft gasification system development
DK	DONG Energy	Co-firing, biorefinery development (bio-ethanol)
DK	Haldor Topsoe	Catalyst development
DK	Novozymes	Hydrolytic enzymes
DK	Risø Nat.lab for sust. Energy	Diverse bioenergy conversion technology development
DK	Genencore/Danisco	Hydrolytic enzymes
ES	Abengoa	Second generation bio-ethanol production
ES	CIEMAT	Diverse bioenergy conversion technology development
ES	Repsol	Biofuel production
F	Air Liquide	Technology for pyrolysis, gasification to second generation biofuels (Bioliq^{TM})
F	ARD, IFP	Biofuel, chemicals production via (bio-) chemical conversion routes
F	Arkema	Biorefinery technology for polymer production
F	CIMV	Biorefinery technology development
F	Renault SA	Support of biofuels production for car implementation
F	Syral	Biorefinery technology development
F	TOTAL	Biofuel production (DME e.g.)
F	Veolia	Energy, water, transportation
FI	Foster Wheeler, Metsö	Biomass gasification technology development
FI	Metso	Biomass gasification technology development
FI	NESTE OIL	Biofuel technology development
FI	Roal Oy	Enzyme development
FI	UPM	Wood conversion (thermo-chemical) to energy and products
FI	VTT	Diverse bioenergy conversion technology development
GR	CERTH	Diverse bioenergy conversion technology development
IT	ENEA	Fuel cell development for biomass derived syngas
IT	ENEL	Power production, co-firing development
IT	ENI	Development of bio-ethanol and FT-diesel routes
NL	Avantium	Catalysis, furanics as biofuels from biomass
NL	DSM-Biopract	Hydrolytic enzymes
NL	Albemarle Catalysts Company BV	Catalysts and chemical conversion
NL	Purac, Gorinchem	Polylactate Plastic production
NL	Large-scale power producing industries: E.ON, EPZ, Essent (RWE), Electrabel, Vattenfall-NUON	Co-firing of biomass

NL	Topell, Stramproy, Foxcoal, 4Energyinvest (BE),…	Torrefaction technology system development
NL	ECN & HVC (waste incineration company)	Bio-CHP and Bio-SNG using MILENA technology
NL	Shell	Biofuel development (gasification and biochemical ethanol production)
NL	BTG	Pyrolysis technology development
NL	ECN	Diverse bioenergy conversion technology development
NL	AFSG-WUR	Diverse bioenergy conversion technology development
NO	Borregaard	Biorefinery technology development
NO	Cambi	Biomass conversion technology development
NO	Norske Skog	Biomass conversion technology development
NO	SINTEF	Biomass thermo-chemical (co-)conversion
NO	Statoil	Biofuel technology development
PL	IEN	Development of biomass (co-)combustion systems
S	E.ON (GoBiGas)	Bio-SNG
S	Chemrec	Gasification technology for pulp and paper industry, thermo-chemical biorefinery technology. www.chemrec.se
S	Innventia / STFI-Packforsk	Biorefinery technology – paper & pulp industry related
S	SEKAB group	Bio-ethanol production
S	Södra	Biofuel (pellets) production
S	Volvo	DME based truck fleet development
S	VVBGC	Pressurized fluidized bed gasification demonstration unit in Värnamo
UK	Alstom Power	Gas turbine development
UK	BP	Biofuel development
UK	Doosan Babcock	Biomass combustion and co-combustion
UK	Johnson Matthey	Catalyst development for syngas upgrading
UK	Porvair	High temperature metal filters for syngas
UK	Velocys (Oxford Catalysts Group)	BTL

Annex III Table 5: Recommendations for Materials Research and Development, Timetable

Thermo-chemical route	**Fuel flexibility**	Challenging fuels, additives, fuel mixes	to enable facilities to use challenging fuels and mixtures	**2011-2015**	**2012-2015**	**2012-2017**	**2013-2017**	**2013-2017**	**2014-2018**	**>2014**
	Slagging, fouling and corrosion	Additives and/or blending of fuels to reduce agressive conditions		**2011-2014**	**2011-2014**	**2012-2015**	**2012-2015**	**2012-2015**	**2016-2018**	**>2016**
		Development of durable/affordable coatings and modelling of material performance and reliable monitoring		**2011-2014**	**2011-2014**	**2013-2015**	**2013-2015**	**2013-2015**	**2016-2018**	**>2016**
	Emissions	Development of poison-resistant catalysts for catalytic de-NO_x systems		**2011-2014**	**2011-2014**	**2013-2015**	**2013-2015**	**2013-2015**	**2016-2018**	**>2016**
	Ash	Deactivation, characterization and use		**2011-2013**	**2011-2013**	**2012-2014**	**2012-2014**	**2012-2014**	**2015-2017**	**>2015**
		utilization of minerals	e.g. making phosphorous in ash available							
	Bio-oil upgrading	Oxygen removal (deoxygenation reactions) and cracking of large aromatics (decarboxylation)	Need to improve resistance to deactivation of the materials used for this purpose: zeolites and mesoporous materials	**2011-2013**	**2012-2014**	**2013-2016**	**2014-2016**	**2014-2016**	**2015-2017**	**>2016**
	Gas cleaning	Tar reduction		**2011-2013**	**2011-2014**	**2012-2015**	**2012-2015**	**2012-2015**	**2015-2018**	**>2015**
		Reduction of NH_3 levels		**2011-2013**	**2011-2014**	**2012-2015**	**2012-2015**	**2012-2015**	**2015-2018**	**>2015**
		Control/disposal of char/ash residues		**2011-2013**	**2011-2013**	**2012-2014**	**2012-2014**	**2012-2014**	**2015-2017**	**>2015**

		Removal of particulates from hot gases	use of hot cyclones and filtration systems	**2011-2013**	**2011-2013**	**2011-2014**	**2012-2014**	**2012-2014**	**2013-2016**	**>2014**
		Extend the lifetime of ceramic and metallic materials of filtration in dedusting syngas at high T	use of alkali species	**2011-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**2017-2020**	**>2020**	**>2020**
	New gasification processes	Further development and testing of structural materials for long term duration in supercritical gasification of wet bio-resources		**2011-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**2017-2020**	**>2020**	**>2020**
	Gasification materials	Corrosion resistant heat exchange materials/coatings	alloy materials, durable ceramic coating	**2011-2015**	**2011-2015**	**2012-2015**	**2012-2015**	**2012-2016**	**2014-2018**	**>2016**
		Oxygen separation membranes		**2011-2015**	**2011-2015**	**2012-2015**	**2012-2015**	**2012-2016**	**2014-2018**	**>2016**
	Downstream	Development of stainless steal alloys to avoid carburization and metal dusting		**2011-2013**	**2012-2014**	**2012-2015**	**2012-2015**	**2012-2015**	**2015-2018**	**>2015**
		Improvement of Fischer-Tropsch catalysts and manufacturing methods		**2011-2015**	**2011-2015**	**2012-2015**	**2012-2016**	**2012-2016**	**2014-2018**	**>2016**
		Deep sulfur cleaning of bio-syngas prior to catalytic upgrading to transportation fuels		**2011-2015**	**2011-2015**	**2012-2015**	**2012-2016**	**2012-2016**	**2015-2018**	**>2016**
	Gas engines and turbines	Improvement of protective and thermal coatings to resist contaminants that cause erosion damage and deposition		**2011-2014**	**2011-2014**	**2013-2015**	**2013-2015**	**2013-2015**	**2016-2018**	**>2016**

	BioCCS	Development of oxygen-carrier materials for novel alternative CCS technologies	Novel CCS technologies: chemical looping combustion, line carbonation/calcination	**2011-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**2017-2020**	**>2020**	**>2020**
	Fuel standardisation	legal actions for new fuel specification	intensive testing necessary							
	Syngas chemistry	platform chemicals with high selectivity through catalytic conversion								
Bio-chemical route	**Substrate pretreatment**	acid-heat treatment, solvent-heat treatment	ideal combination with mechanical pretreatment; new methods for fibre disintegration, partial hydrolysis etc.	**2011-2016**	**2011-2016**	**2011-2016**	**2011-2016**	**2011-2013**	**2011-2013**	**2014-2016**
	Enzymatic substrate hydrolysis	New enzymes for more effective hydrolysis of polymeric sugars in biomass and their production	new enzyme producing microorganisms and new enzymes	**2011-2013**	**2011-2014**	**2011-2014**	**2014-2016**	**2014-2016**	**2014-2017**	**>2017**
		Microorganisms for production of recombinant enzymes		**2011-2013**	**2011-2013**	**2011-2014**	**2014-2016**	**2017-2020**	**2017-2020**	**>2020**
		new solvents (ionic liquids)		**2011-2013**	**2011-2013**	**2014-2016**	**2014-2016**	**2014-2016**	**2017-2020**	**>2020**
		new materials resistant to low conc. acid	teflon or ceramics coating etc.							
	Catalytic substrate hydrolysis	Hydrolysis with heterologous catalysts - cell wall polysaccharides to sugars	Polysaccharides could even be further hydrogenated with specific catalysts to chemicals and energy carriers	**2011-2013**	**2011-2013**	**2014-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**>2020**
	Removal of toxic byproducts of pretreatment	Adsorbents for or separation of toxic byproducts of pretreatment and thermo-chemical hydrolysis	chemicals such as furfurals have to be removed prior to fermentation; furfurals potentially are a valuable byproduct	**2011-2013**	**2011-2013**	**2014-2016**	**2014-2016**	**2014-2016**	**2017-2020**	**>2017**

	New products of fermentation	new microorganisms with high product yield, high process stability, enhanced product selectivity, alternative products (such as butanol), enlarged substrate utilization	eventually by genetical engineering; includes fermentative and photosynthetic MOs;	**2011-2013**	**2011-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**>2020**	**>2020**
	Thermophilic fermentation	higher temperature for higher turn-over rates, less contamination, higher product selectivity	challenges are product intolerance of producing MOs; corrosion on equipment; thermostable insulation, tubings, fittings etc	**2011-2013**	**2011-2013**	**2014-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**>2017**
	New fermentation types	Solid state fermentation, utilization of immobilized cells, continuous fermentation, in-situ separation of product	R&D needed for process handling, monitoring equipment and methods, new producer strains, immobilization materials etc	**2011-2013**	**2011-2013**	**2014-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**>2020**
	Photosynthetic processes	CO2 utilization and sequestration for production of oils/lipids or hydrogen	includes new microorganisms as well as light-incubators	**2011-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**2017-2020**	**>2020**	**>2020**
	Product separation from fermentation	separation of biofuels from diluted broths and from the producing MOs	equipment for vacuum; materials like membranes or adsorbents	**2011-2013**	**2011-2013**	**2014-2016**	**2014-2016**	**2017-2020**	**2017-2020**	**>2017**
	Catalytic product conversion	transesterification of lipids	new catalysts		**2011-2013**	**2011-2013**	**2011-2013**	**2011-2013**	**2014-2016**	**>2014**
		converting fermentation products to biofuels	new catalysts	**2011-2013**	**2011-2013**	**2014-2016**	**2014-2016**	**2014-2016**	**2017-2020**	**>2017**
	Gas purification	removal of CO2 from biogas	to produce methane		**2011-2013**	**2011-2013**	**2011-2013**	**2011-2013**	**2014-2016**	**>2014**

Basic research actions (*specify if a programme is necessary or a project or a research infrastructure, including modelling*) to research new ideas or scientific principles that may be one day at the onset of a new material and/or constitute a breakthrough for the next generation of an existing technology/material.

Applied research actions *(specify if a programme is necessary or a project)* focused at proving the concept and improving materials and manufacturing processes as well as transforming basic science discoveries into functional materials/manufacturing processes.

Pilot actions - This consists mainly of initial small scale trials of new materials and manufacturing techniques straight out of the research laboratory. The results of this type of effort are proof of feasibility and assessment of material components operability.

Reference Test facilities and pre-normative research: to validate/test, standardise reference materials/components and/or production

Demonstration actions - This constitutes the actual trial and large scale demonstration, and is particularly relevant to prove the full-scale viability of the materials and the manufacturing. This includes measures for coordination, knowledge and information exchange, etc.

Market measures -
Standards setting etc.

In terms of timing for implementation of the proposed research actions, we propose the following timelines: 0 to 3 years or 3 to 6 years or 6 to 10 years. The goal is to have a balanced approach with respect to the implementation of the recommendations/roadmap in the next 10 years. Not all actions should be executed during the first year.

European Commission

EUR 25154 EN – Joint Research Centre – Institute for Energy and Transport
Title: Scientific Assessment in support of the Materials Roadmap enabling Low Carbon Energy Technologies
Author(s): Wolfgang H. Schwarz, Orlando José Gonzalez Bello, Wiebren de Jong, J.J. Leahy, John Oakey, Karin Oyaas, Lars Sorum, Horst Steinmüller
JRC Coordination: David Baxter, Evangelos Tzimas

Luxembourg: Publications Office of the European Union
2011 – 56 pp. – 21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1831-9424 (online) , 1018-5593 (print)
ISBN 978-92-79-22680-9 (pdf)
ISBN 978-92-79-22679-3 (print)

doi:10.2790/40833

Abstract

This scientific assessment serves as the basis for a materials research roadmap for bioenergy technology, itself an integral element of an overall "Materials Roadmap Enabling Low Carbon Technologies", a Commission Staff Working Document published in December 2011. The Materials Roadmap aims at contributing to strategic decisions on materials research funding at European and Member State levels and is aligned with the priorities of the Strategic Energy Technology Plan (SET-Plan). It is intended to serve as a guide for developing specific research and development activities in the field of materials for energy applications over the next 10 years.

This report provides an in-depth analysis of the state-of-the-art and future challenges for energy technology-related materials and the needs for research activities to support the development of bioenergy technology both for the 2020 and the 2050 market horizons.

It has been produced by independent and renowned European materials scientists and energy technology experts, drawn from academia, research institutes and industry, under the coordination the SET-Plan Information System (SETIS), which is managed by the Joint Research Centre (JRC) of the European Commission. The contents were presented and discussed at a dedicated hearing in which a wide pool of stakeholders participated, including representatives of the relevant technology platforms, industry associations and the Joint Programmes of the European Energy Research Associations.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

JRC
EUROPEAN COMMISSION

LD-NA-25154-EN-N

Publications Office

ISBN 978-92-79-22680-9

9 789279 226809