BIOMASS BASED ENERGY INTERMEDIATES BOOSTING BIOFUEL PRODUCTION

A EUROPEAN RESEARCH PROJECT ON RENEWABLE ENERGIES

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ABSTRACT

Converting residual biomass into high energy density intermediate energy carriers for heat, electrical power, transportation fuels and chemicals production is the aim of the collaborative EU-project BioBoost (Biomass based energy intermediates boosting biofuel production). Exemplary, BioBoost investigates three promising conversion pathways for several residual biomass feedstocks which are converted by fast pyrolysis, catalytic pyrolysis or hydrothermal carbonisation to intermediate energy carriers for subsequent use in different applications. A heuristic transportation model is being developed and integrated into the environmental and economic assessment. The applicability of the different energy carriers is investigated in existing and upcoming applications for heat and power production, synthetic fuels and chemicals production as well as bio-crude for refineries. The project combines complementary expertise from 13 partners of six member countries representing research institutions, chemical industry, and energy suppliers. The collaborative BioBoost project is coordinated by the Karlsruhe Institute of Technology (KIT) and is funded by the 7 Framework programme of the European Union under grant agreement 282873 (www.bioboost.eu).

To increase the share of biomass for renewable energy supply in Europe conversion pathways which are low cost and energy efficient, as well as flexible in feedstock are demanded. The BioBoost project aims to make a substantial improvement towards increasing the efficiency of the use of biomass and organic residues in the future. The project focuses on de-central conversion of biomass to optimised, high energy density carriers, which can be utilised either directly in small scale combined heat and power (CHP) plants or in large scale applications for the synthesis of transportation fuels and chemicals. Dry as well as wet residual biomass and organic waste are used as feedstock for conversion. Due to their secondary nature, these feedstocks have the potential for high environmental sustainability, and in the case of straw, it may even strengthen food production than competing to it. However, perennial lignocellulosic energy crops and forest residues are included as a possibility to compensate the seasonal occurrence of for example straw. In the BioBoost project, these types of biomass are converted by means of fuel-flexible thermo-chemical processes such as fast pyrolysis, catalytic pyrolysis and hydrothermal carbonisation (HTC) to produce stable, intermediate energy carriers in the form of bio-oil, bio-coal or bio-slurries (biosyncrude). For straw, as an example, the energy density of the carrier can be increased by a factor of 10 to 15, enabling economic long range transportation from several regionally distributed conversion plants to few central large scale gasification plants for bio-fuel production.

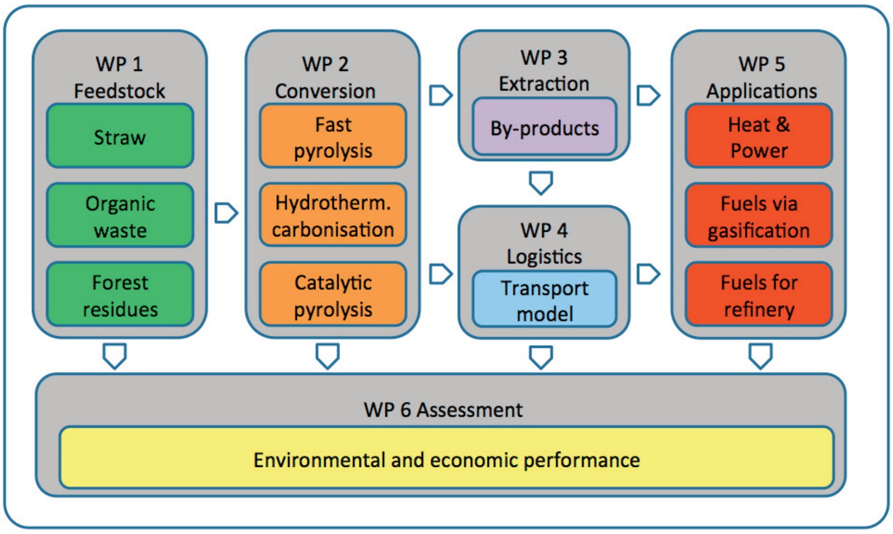

Fig. 1: BioBoost project structure and scientific/technical work packages

A logistic model of the supply chain taking into account de-central and central conversion scenarios with different types of energy carriers is set up and validated allowing the determination of minimum costs, the number and location of de-central and central conversion sites. A techno-economic and environmental assessment of the value chains supports the optimisation of processes and products and allows for comparison of the processes under consideration and to other conversion routes. The application of energy carriers is investigated with partners from industry for heat and power production, synthetic fuels & chemicals, and as bio-crude for refineries. Coordinated by the Karlsruhe Institute of Technology (KIT) 13 partners from industry, universities and research institutions take part in the collaborative project, contributing the main objectives:

- To develop supply concepts of residual biomass for de-central conversion plants

- Convert biomass to intermediate energy carriers

- Improve the economic performance of the energy carrier by investigating methods for the recovery of high value chemicals and nutrients from pyrolysis condensates and HTC process water

- Optimised biomass and energy carrier logistics

- Clarify and test the technical and economic utilisation paths of energy carrier

- Investigate the techno-economic feasibility and environmental sustainability of bio-energy carrier pathways.

Accordingly, the main research areas are structured in work packages as depicted in Fig. 1:

- Identification of residual biomass potential in EU-28 and development of supply concepts of for de-central conversion plants (WP1)

- Conversion of biomass to intermediate energy carriers by thermo-chemical processes (WP2)

- Improvement of the economic performance of the energy carrier by investigating the recovery of high value chemicals and nutrients from conversion processes (WP3)

- Development of a simulation model optimising biomass and energy carrier logistics (WP4)

- Clarification and testing the technical and economic utilisation paths of energy carrier (WP5)

- Investigation of the techno-economic feasibility and environmental sustainability of the selected bioenergy carrier pathways (WP6)

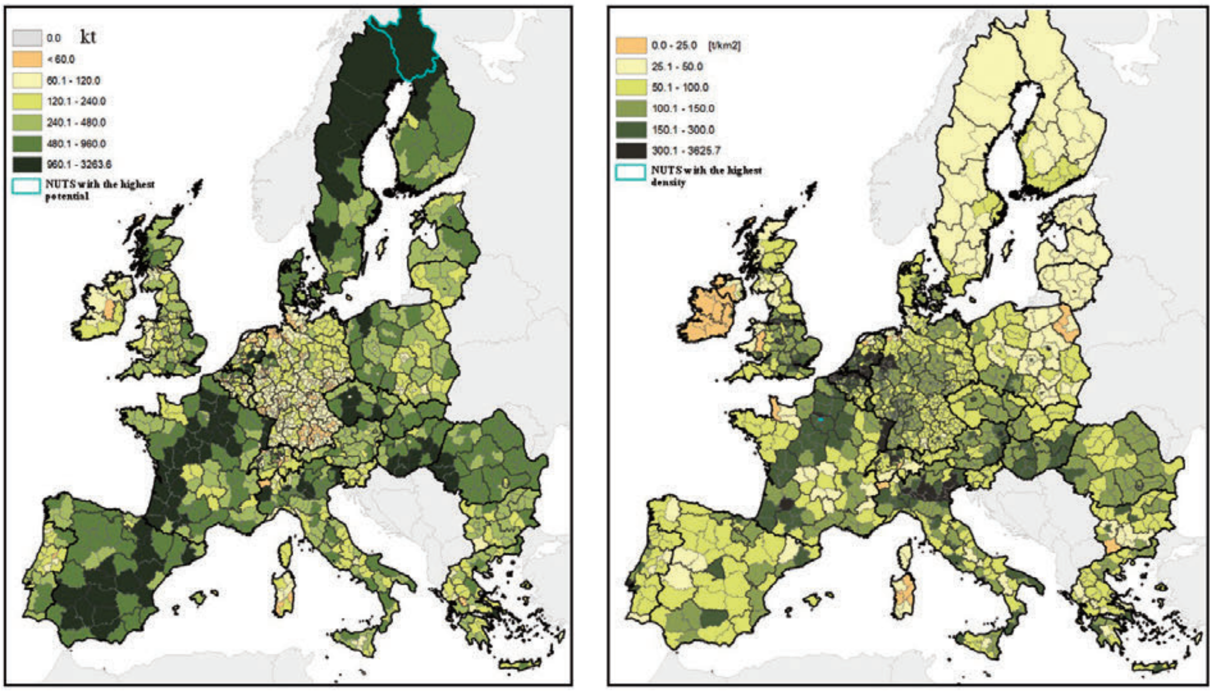

Fig. 2: Total technical biomass potential (left) and total density of biomass (right) in EU-27 and Switzerland

FEEDSTOCK POTENTIAL AND SUPPLY COSTS

The conversion technologies fast pyrolysis, catalytic pyrolysis and hydrothermal carbonisation studied in the BioBoost project make us of a broad feedstock spectrum of lignocellulosic materials from dry to wet. Suitable biogenic resources occur in various residue and waste streams from agriculture, forestry, land cultivation and management, food processing and settlement. Consequently, in BioBoost the feedstock potential of agricultural residues, organic wastes and forestry residues in EU-27 + Switzerland has been raised considering the following types of biomass:

- Agricultural (straw, orchard's pruning, hay) and animal residues (manure),
- Forestry residues,
- Natural conservation matter (urban maintenance of green areas, hay and shrubs),
- Roadside vegetation,
- Urban and industrial waste (biodegradable municipal waste, selected waste from the food and wood industry).

The estimates were conducted at IUNG for geocode standard NUTS-3 areas. In BioBoost, such a comprehensive EU wide review has been carried out in such spatial scale for the first time. The regional NUTS-3 level provides the typical scale for the development of distributed energy scenarios. The main pre-condition for the potential modelling of these regions was to use only waste and residues biomass, which do not compete with food production and to respect the principles of sustainable production and environmental protection. The modelled results of the biomass potential have been illustrated by maps of theoretical and technical potentials in the NUTS-3 regions (see Fig. 2). Additionally, normalised potentials were developed for visualisation of the biomass density and spatial variability in larger regions. On this basis the amount of biomass and its spatial density and energy content is raised. The largest potential of biomass is provided by straw with a share of 37% related to mass and of 48% regarding the energy content. The second largest potential can be generated from forestry residues (29%, both in terms of mass share and energy content). Another promising resource is biodegradable municipal waste (17% of the biomass and 12% of the energy content). Other types of biomass do not have much significance in the European energy sector. In certain areas, individual types of biomass may play a regional role. All data on biomass potential will be made available via a Geographic Information System (GIS Server) and are included in the logistic optimisation model, which also will become available as a internet tool.

For the techno-economic assessment, biomass supply costs are mandatory. In BioBoost reference has been made to published information by SYNCOM. As can be expected, results of biomass provision costs considerations are, that use of waste is more economic than use of residues, that dry feedstocks is more expensive than wet ones (on an energy basis), and that ash-rich feedstocks are more economic than low-ash types of biomass, if appropriate technology is available for their treatment.

Straw collection was assessed as difference to leaving it on the field in terms of fertilizer withdrawal and replacement costs, baling and bale chasing technology as well as implications of field size, straw amount and labour costs. Applying the most efficient technology for the supply of several ten- to hundred-thousand tonnes to de-centralised conversion plants leads to straw costs free field side stack between €31 and €39 per tonne. This is in contrast to average prices between €20 and €180 per tonne recorded in 2011. The harvest of forestry residues like thinning wood, slash and stumps was oriented at the example of the countries like Sweden and Finland, more advanced and experienced in that area. This information has been complemented by information on the forestry in the other European countries and wood chip prices free forest road. Prices raised are between about €25/odt (oven dry tonne) for low quality residues and €80 to €100 for high quality wood chips.

To make residues available in an economic way also, the harvesting and collection system has to be improved. A versatile system of a forestry mulcher coupled to a round baler is suggested e.g. in case of landscape maintenance, clearing of road side green or power line tracks, and pruning residues. The rough cut, round-baled biomass air-dries in road side stacks and the respective chips cost between €66 and €81/odt, depending on the terrain biomass density and forwarding distance. Organic wastes from municipalities or food processing have a waste yard gate fee of €-60 to €-20 per tonne (€-200/odt at 70% moisture) to cover the costs for composting, depending on the system and purity of the waste; Incineration is typically more expensive. Waste wood has gate fees typically between €-60 per tonne of contaminated or treated wood up to €15 per tonne of untreated wood, this is dependent on the region and the season however. Europe has regions, where the manure from livestock rearing exceeds the amounts which may be land-spread. In these surplus regions between €5 and €25 per tonne are paid for the manure removal, either to processing plants or to areas of low cattle density.

THERMO-CHEMICAL BIOMASS CONVERSION

Thermochemical processes make use of temperature to decompose organic matter into gaseous, liquid or solid products. These can be utilised as intermediate energy carriers for heat, electrical power or fuels production. Thermochemical processes allow for a broad range of feedstocks, making them fuel flexible and scalable for high conversion capacities. For transportation, liquid and solid energy carriers of high energy density are favourable. Consequently, for the BioBoost value chains complementary thermo-chemical processes have been selected in regard to feedstock type and energy carrier application. From fast pyrolysis, catalytic pyrolysis and hydrothermal carbonisation solid and liquid fuels are obtained, which can be used in different applications. In BioBoost exemplary conversion pathways have been agreed making us of different types of feedstocks, producing diverse energy carriers suitable for different applications (Table 1). In all processes, the feedstocks selected were converted in pilot plants of

Process	Feedstock	Energy carrier	Application
Fast pyrolysis	Straw, miscanthus, scrap wood	Char, bio-oil, pump- and flowable slurry of both bio-oil and char	Separate combustion of bio-oil and char and gasification (slurry)
Catalytic pyrolysis	Beech wood, miscanthus, straw	Low oxygen content catalytic bio-oil	Refinery feed to produce transportation fuels
Hydrothermal carbonisation	Organic municipal waste, spent brewery grain	Bio-coal	Heat and power production

Table 1: Conversion pathways addressed in BioBoost

representative size under optimum conditions. For the products obtained in the conversion experiments conducted, mass yield, energy content and fuel properties have been determined along with storage and transportation properties including safety aspects and transportation risks. The energy carrier specifications relevant for combustion and gasification were identified by the industrial partner ENBW.

FAST PYROLYSIS

The objective of the tasks on fast pyrolysis was to optimise the technical setup and operating conditions of the conversion facilities for pyrolysis of dry feedstocks towards an energy carrier suitable for gasification and subsequent synthesis to transportation fuels. Besides this reference pathway, the goal was to develop a flexible pyrolysis process that can provide different energy carriers for energetic use helping to introduce the technology to the market. For that purpose separate combustion tests for char and bio-oil are conducted at University of Stuttgart. At KIT, test facilities for the fast pyrolysis of biogenic residues exist on lab-, bench- and pilot-scale. Both the bench-scale (10 kg/h biomass feed) and the pilot scale unit (500 kg/h biomass feed) make use of a twin screw mixer reactor (Fig. 3).

Pyrolysis experiments have been conducted with three types of biomass, wheat straw, miscanthus and scrap wood. The results from the mass, carbon and energy balances have been set up for all cases. The yield of

Fig. 3 : Reactor of the fast pyrolysis pilot plant at KIT

slurries (bio-oil plus char) is practically the same for all three biomasses. From 1 kg of a completely dried biomass, between 0.75 to 0.8 kg of slurry can be derived. However, the chemical properties vary strongly, especially in terms of solid and therewith ash content. From wheat straw, having an average ash content of ca. 10 wt.%, the slurry with the highest char and ash content (27 wt.% and 11 wt.%) is obtained. This slurry contains about 18 wt.% of water and has a higher heating value above 16 MJ/kg. Scrap wood yields the slurry with the highest heating value (above 20 MJ/kg) due to low ash and water contents. For moist feedstock, the water contents of slurries increases, whereas its solid content and heating value decreases. Thus, the heating values range between 18 MJ/kg and 14 MJ/kg, water contents of 25-31 wt.% and solid contents of 15-25 wt.%.

Fig. 4: Pilot plant for catalytic pyrolysis at CERTH

CATALYTIC PYROLYSIS

As the second conversion technology, the catalytic pyrolysis was optimised by CERTH towards the production of catalytic bio-oil that has a maximum product yield related to the biomass feed capacity with a minimum oxygen content. This bioenergy carrier can be used for the production of transportation fuels in an existing refinery infrastructure. The optimisation work performed in this work aims at optimised catalytic materials, suitable feedstock types and process operating conditions. GRACE company performed the catalyst synthesis and catalyst scale up while at CPERI the catalyst pre-screening and the process optimisation studies on pilot scale were carried out. Fifteen new catalytic materials were synthesised by GRACE and tested at CERTH on bench scale catalytic pyrolysis tests. From this pre-screening study the three best catalysts were selected and scaled up at GRACE in sufficient amounts for pilot scale testing. The new catalysts and five commercially available catalysts were tested in a pilot plant (Fig. 4) after a steam deactivation procedure. It was concluded that the best BioBoost catalyst performs better than the state of the art commercial catalyst producing about 1-2 wt.% more oil at the same oxygen yield. This result was fully validated using the other biomass feedstocks, too. It was concluded that this catalyst is an optimum catalyst for this process. Regarding the feedstock, the woody biomass turned out to be the best followed by the energy crop (miscanthus) and the agricultural residue (wheat straw). Regarding process optimisation the catalyst to biomass ratio (C/B) plays a significant role since with excess catalyst the energy carrier is decomposed and the yield is decreasing again. The pilot plant has been operated satisfactory with C/B ratios in the range of 12-20. It was also proved that the catalyst deactivation plays an important role on the catalyst performance. Both hydrothermal deactivation and ash metal poisoning have a strong detrimental effect on catalyst stability and performance. Sufficient amounts of catalytic bio-oil were produced from the various catalysts and feedstocks and were fully characterised using routine and advanced characterisation methods like 2DGC-TOFMS. Larger quantities of this carrier were handed over to NESTE company for further downstream upgrading processes.

HYDROTHERMAL CARBONISATION

First, screening experiments on hydrothermal carbonisation (HTC) with batch micro-autoclaves have been performed at KIT to find optimum conversion conditions. Important findings are that the nature of the feedstock as well as pre-heating has an important impact on the reaction. This and other observations lead to the development of a kinetic model. This model is able to describe the reaction kinetics of different biomass feedstocks. The screening of biomass conversion and the kinetic model lead optimised operation of the HTC process at AVA-CO2´s test facilities (Fig. 5). Here, experiments with brewery spent grains and organic municipal waste in a bench-scale (K3) and industry size (HTC0) reactor were performed. Surprisingly, the heating values achieved in these experiments were higher than that in the micro-autoclaves. Therefore, a new laboratory plant was constructed at KIT; first results show good accordance with the results of AVA-CO2. Scale-up tests of AVA-CO2 basically proved the validity of KIT's

Fig. 5: Pilot plant for hydrothermal carbonisation at AVA-CO2

kinetic model. Regarding the whole process chain from biomass to end product, there are many parameters and factors which are have to be optimised:

- Nature of biomass, in particular municipal waste: using it untreated would save expensive, additional cleaning steps, but leads to low heating values and causes technical problems (blockage of valves, piping etc.); even chopping improves only technical handling but not the energetic result.

- Mixing low energetic biomasses, e.g. brewery spent grains with a low dry matter content with waste straw (even in mixed forms like in horse dung) offer a large potential for optimisation of biomass use cases and optimised energetic content of the bio-coal.

- A huge potential for optimisation is on the downstream side of the HTC process, i.e. separation and drying of the coal and the handling of the process water (including recycling).

EXTRACTION OF VALUABLE BY-PRODUCTS

In BioBoost, there is a strong focus on the economics of the processes. To improve the economics of the overall value chains the extraction of chemical by-products from the pyrolysis products and the HTC process were investigated by DSM in co-operation with other BioBoost partners. For the isolation of mixtures of phenol derivatives (so-called phenolics) CERTH developed several different extraction schemes depending on the source of starting material KIT fast pyrolysis oil or CERTH catalytic pyrolysis oils. When starting with fast pyrolysis bio-oil an extraction with an organic solvent yields a final fraction consisting of 14.6 wt.% phenolics with 80 % extraction efficiency. The enrichment achieved is satisfying, especially considering the low concentrations of phenolics in the bio-oil used as feed. Catalytic pyrolysis bio-oil has a far higher concentration of phenolic compounds and multi-stage processes is developed for their efficient extraction. Experiments at CHIMAR showed that bio-oils from pyrolysis could be used in the synthesis of phenol-formaldehyde resins suitable for the production of plywood and particleboard panels.

For the isolation of furfurals (HMF, hydroxy-methylfurfural, one of the most important chemical platform molecules from biomass) from the aqueous stream of the HTC process two methods were investigated. A first approach is the solvent extraction for which different solvents were screened on their partition coefficients, mutual solubility in the aqueous phase and the physical phase separation properties. Chloroform showed promising extraction properties and was successfully tested on a 8-stage mixer settler battery. Also, the adsorption of HMF to activated charcoal and the following desorption was tested. When optimised towards the production of bio-coal, the amount of furfural in the HTC process water is insufficiently low for extraction. It was found out, that furfurals are the chemical precursors of the bio-coal and therefore are only present in low concentrations, when bio-coal is the target product.

LOGISTICS

Within the BioBoost project optimisation of transportation and handling of biomass feedstock and of bioenergy intermediates carriers are key issues as part of the assessment of the whole bioenergy value chains. The primary focus of the project is on conversion technologies for decentralised conversion of biomass to bioenergy intermediates and subsequent energy production on a trans-regional, EU-wide level. Transport of biomass over long distances is relatively expensive; therefore, de-central conversion plants should be located in regions with large feedstock potentials. In BioBoost the viability of

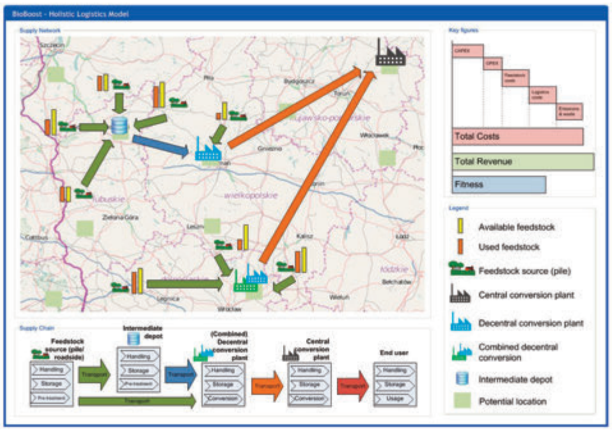

Fig. 6: Concept of the logistics model

decentralised conversion of biomass to intermediates energy carriers using optimised transport logistics for feedstock and intermediates is investigated on the basis of regional biomass potentials, data on transportation modes and costs as well as on data on the conversion technologies applied. The holistic logistics model developed by FHOOE simulates and optimises biomass and energy carrier transportation regarding costs and CO2 emissions as well as suitable identifies optimal locations for decentralised and central plants (Figure 6). Uneconomical transportation e.g. of highly water containing types of biomass residues featuring low energy contents favour a decentralised supply network which have short pre-haulage distances. The model is used to calculate resulting total costs for given scenarios which describe locations and capacities of de-central conversion plants, as well as the amounts of acquired feedstock and transportation targets.

ASSESSMENT

The assessment methodology and the reference pathways were defined in order to assess the techno-economic, environmental and social aspects of pre-defined bio-energy carrier reference pathways agreed among the BioBoost partners (Fig. 7). Based on this methodology, a data questionnaire was developed and completed by all data providers. A first assessment was completed by TNO for the reference pathways and the results were validated in collaboration partners. Also, it includes the definition of key performance indicators based on international and European frameworks, the data inventory, benchmarks and assessment procedures. Based on these resources and the data provided by the consortium partners on logistics, feedstock properties, and conversion technologies, TNO executes the assessment study. The backbone for the BioBoost assessment methodology is the GBEP framework. The Global Bioenergy Partnership (GBEP) developed a set of indicators for policymakers and stakeholders to guide the development of the bioenergy sector and to meet international goals on sustainable development. These sustainability indicators are science-based and refer to environmental, social, and economic aspects. They were based on earlier roadmaps on biofuels by the International Energy Agency (IEA). Practically, the themes from GBEP were used to identify and evaluate the Key Performance Indicators (KPI) which are used to express BioBoost's assessment results.

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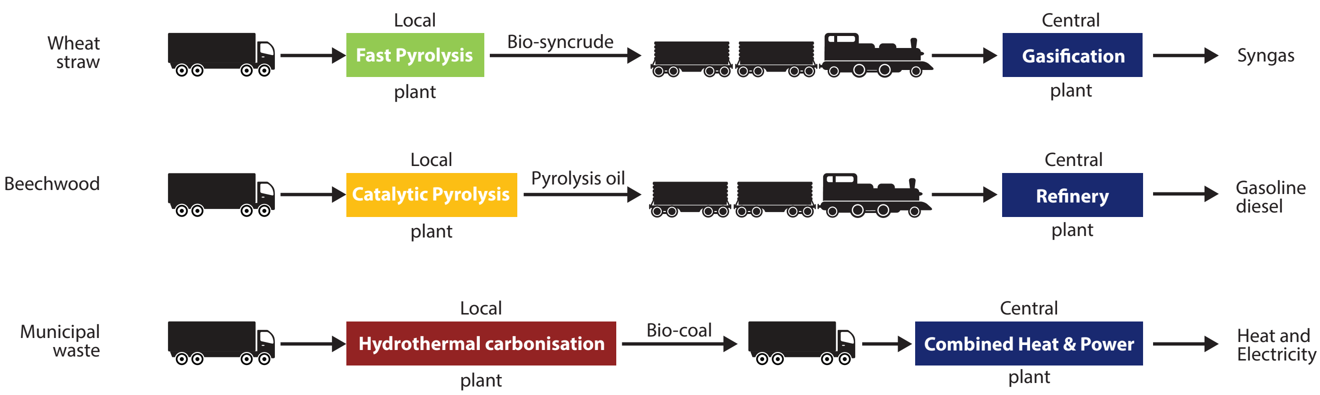
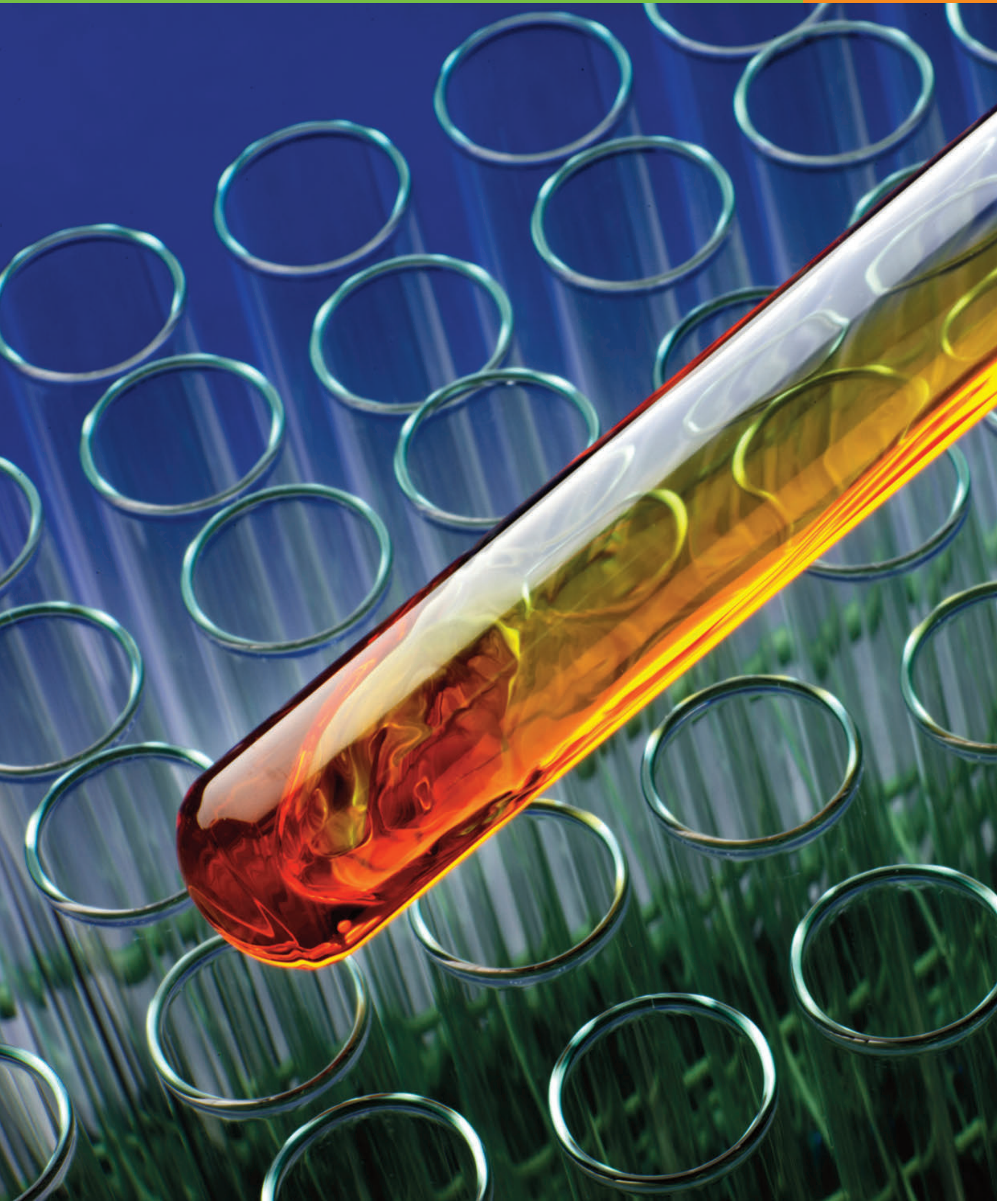


Fig. 7: Reference pathways considered in the assessment studies



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