

The bioliq process for producing synthetic transportation fuels

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Biofuels of the second generation can contribute significantly to the replacement of the currently used fossil energy carriers for transportation fuel production. The lignocellulosic biomass residues used do not compete with food and feed production, but have to be collected from wide-spread areas for industrial large-scale use. The two-stage gasification concept bioliq offers a solution to this problem. It aims at the conversion of low-grade residual biomass from agriculture and forestry into synthetic fuels and chemicals. Central element of the bioliq process development is the 2–5 MW pilot plant along the complete process chain: fast pyrolysis for pretreatment of biomass to obtain an energy dense, liquid intermediate fuel, high-pressure entrained flow gasification providing low methane synthesis gas free of tar, hot synthesis gas cleaning to separate acid gases, and contaminants as well as methanol/dimethyl ether and subsequent following gasoline synthesis. After construction and commissioning of the individual process steps with partners from industry, first production of synthetic fuel was successfully achieved in 2014. In addition to pilot plant operation for technology demonstration, a research and development network has been established providing the scientific basis for optimization and further development of the bioliq process as well as to explore new applications of the technologies and products involved. © 2016 John Wiley & Sons, Ltd

INTRODUCTION

Only 200 years ago, the energy supply of a 1 billion world population depended nearly entirely on renewables. The main energy source was firewood for residential heating, cooking, and lighting, also serving for high-temperature manufacturing processes such as iron ore reduction, burning bricks and tiles, or glass melting. Not to forget that the main power source for human activities carried out by working animals has been fuelled by biomass. Today, a world population of more than 7 billion people

consumes around 600 EJ/a primary energy.¹ The current world primary energy mix consists of ca. 80% fossil fuels and little more than 10% of bioenergy. Toward the end of the century, an increase of the world population to a maximum of almost 10 billion is expected in combination with a doubling of the energy consumption to about 1200 EJ/a. If the high fossil fuel share is maintained in the future energy mix, the proven and economically recoverable overall coal, oil, and gas reserves will be depleted in about a century. In this scenario, the present CO₂ content of 386 ppmv in the atmosphere is expected to double causing global warming of several Kelvin and raising sea levels as well as more frequent extreme weather excursions are to be expected.

To gradually replace the dwindling fossil fuels in the course of this century, renewable energies must be further developed to commercial maturity. The inevitable switch-over of the energy system requires much financial effort, time, and innovative ideas

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heavily straining human and material resources. Biomass must and can contribute an indispensable and significant part to a sustainable future energy supply, but it can by no means serve all energy needs of mankind. A future share of 10–20% would mean the use of 2–4 times more biomass than at present. Special attention has to be paid to technology research and development for the exploitation of biomass as the only renewable carbon source for organic chemicals and fuels. The most abundant constituent of terrestrial plants is lignocellulose, a composite material consisting of natural polymers (Box 1). Any large-scale biomass utilization must rely on this most available bio-carbon material; starch, sugar, oil, and protein in food crops have to be used as human or animal food or feed as highest priority. The second priority is stem wood utilization as organic construction material as well as the production of organic raw materials such as cellulose fibers from wood or cotton. In regard to energetic use, biomass worldwide is predominantly used for heating and cooking purposes by combustion. Also in developed countries, biomass combustion for heat and electricity generation today appears to be more economic than using lignocellulosic bio-carbon for more advanced applications by gasification or fermentation. In the future, when fossil hydro-carbon reserves become more expensive or exhausted, applications utilizing biomass feedstock will increasingly gain higher priority. By all other renewable energy sources, heat or electricity can directly be generated, but no carbon products. In some cases, carbon based energy production is difficult to replace, in particular in the transportation sector. Even considering an increased degree of electrification in mobility, a significant share of liquid hydrocarbon fuel will be

BOX 1

LIGNOCELLULOSIC BIOMASS

Lignocellulose is the abundant construction material of the cell walls of all terrestrial plants and contributes almost 90% to the available land biomass. Its use in the form of residues and wastes in agriculture, forestry, and industry is not in direct competition to food and feed production and therefore a versatile feedstock for second generation biofuel production. The simplified average composition is about 40–55 wt% cellulose fibers, 15–35 wt% hemicellulose and 20–40 wt% lignin represented by $C_6H_8O_4$ as approximate sum formula.

needed at least for aviation, marine transport, and for car and truck transports in remote areas.

Synthesis gas (syngas) obtained from gasification (Box 2) is a versatile and flexible platform to convert organic feedstocks including natural gas, coal, organic waste, and biomass into chemical building blocks from which a broad variety of different synthetic chemicals and fuels can be derived. In comparison to the use of fossil energy carriers, the production of syngas from biomass is more complex and, consequently, more expensive today. For the industrial utilization of biomass fuels on a large scale, several hurdles exist:

- *Logistics.* Biomass accumulates over large areas and therefore has to be collected and transported over long distances for large-scale use. In particular, less valuable biomass such as straw or forest wood residues have a low volumetric energy density (conventionally baled straw ca. 2 GJ/m³ in comparison to 36 GJ/m³ for diesel fuel).
- *Heterogeneity.* A large variety of potentially usable biomass materials exist, differing in chemical composition, availability, storability, and so on. For their use, feed-flexible processes are required.

BOX 2

PYROLYSIS AND GASIFICATION

Pyrolysis and gasification are thermochemical processes by which organic material such as coal, refinery residues, or biomass are decomposed by help of temperature. Pyrolysis carried out in the absence of oxygen leads to liquid, solid, and gaseous products, the yields of which depend on temperature and reaction time. Fast pyrolysis aims at maximum liquid yields by very short reaction times and temperatures around 500°C. By gasification, a fuel is reacted at even higher temperatures typically above 800°C to gaseous products by means of a gasification agent, which can be air, pure oxygen, steam, or CO₂. When oxygen is applied the energy required to heat up the reactor is obtained by partial oxidation of the fuel. At temperatures above 1000°C, clean (i.e., tar free) syngas, a mixture of H₂ and CO, is obtained suitable for chemical conversions.

- *Quality.* Syngas-based chemical processes require a tar-free, low-methane syngas at pressures of 30–80 bar and demand for extensive elimination of trace impurities which would act as catalyst poisons. However, this facilitates meeting the stricter exhaust emission norms when synthetic fuel is burned.
- *Efficiency.* Biomass materials, with their average chemical composition of $C_6H_9O_4$, yield a C/H ratio close to 1 on gasification, which is insufficient for the production of hydrocarbons. This requires an additional process step, the water–gas shift reaction, in which through addition of water, a fraction of the CO is converted into hydrogen and CO_2 . This leads however to reduced carbon efficiency. In the long term, it will be expedient to fill the additional hydrogen requirements by utilizing other renewable energy sources.
- *Sustainability.* The biomass is taken from the biosphere which must be accomplished in an ecologically compatible and sustainable manner. Beyond, the use of biomass has to consider additional socioeconomic aspects, because the new role for arable land, grassland, and forests as providers of energy raw materials requires the establishment of new logistics, income, and labor structures and must not lead to an irreparable loss of land area, diversity, and quality.
- Decentralized pretreatment of biomass for energy densification in a number of regionally, distributed plants to mobilize a large mass potential at reasonable transportation costs for central gasification and synthetic fuels or chemicals production.
- Taking advantage of technologies already being state of the art or where industrial experience was available for process development.
- Scalability of the selected technologies, i.e., pretreatment technologies up to 100 MW and gasification (modules) up to 500 MW thermal fuel capacities.
- Efficient conversion processes in order to reduce specific investment costs, e.g., by gasification at elevated pressures fairly above those required by the subsequently following synthesis process to avoid expensive gas compression or by applying hot syngas cleaning at a high temperature level to allow for efficient heat recovery with purified syngas.
- For high pressure feeding, liquids are most suited. Therefore, fast pyrolysis was selected as pretreatment process. The high yields of liquid condensates and char are mixed to energy rich slurries (biosyncrude) as gasification fuels maintaining as much of the energy originally contained in the biomass.
- As synthetic fuel gasoline was chosen according to methanol-to-gasoline (MtG) process developed in the 1980s. Instead of methanol, a one-step synthesis for dimethyl ether (DME) is being developed as intermediate on the way to further conversion to gasoline and other products.

At Karlsruhe Institute of Technology (KIT), the bioliq biomass-to-liquid (BtL) process is developed intending to overcome these logistical, technical, and related hurdles.

CONCEPT OF THE BIOLIQ PROCESS

The bioliq process development essentially is the result of an interdisciplinary panel at KIT discussing on the potential use of biomass residues for energy production end of the 1990s. Among others, the potential competition to food and feed production by biofuels turned out to be a most determining issue. As a consequence, the increased use of nonedible parts and coproducts of biomass production from agriculture and forestry was considered for energetic use.² Consequently, a concept was derived for the use of the available amounts of low grade, residual biomass for use in large-scale synthetic biofuels production. First denoted as Karlsruhe BtL2 and later as bioliq, the concept was first committed to a paper in 2002.^{3,4} Main considerations and aims have been given as follows:

A full description of the bioliq process concept is given by the authors elsewhere.⁵

BIOLIQ PILOT PLANT CONSTRUCTION AND OPERATION

The bioliq pilot plant project has been realized by three successive steps between 2005 and 2013. The complete process chain was constructed in cooperation with partners from industry for each major process step. The pilot plant after completion is shown in Figure 1 with fast pyrolysis and biosyncrude production plant (left side), tank farm (middle), gasifier, syngas cleaning, and outdoor synthesis plant (right side).

In 2005, the first of the three projects started with the construction of the fast pyrolysis pilot plant



FIGURE 1 | Image of the bioliq pilot facility.

as pretreatment process for biomass liquefaction. Fast pyrolysis means rapid heating up of biomass particles by contact with a hot heat carrier (sand) and immediate cooling down of pyrolysis vapors formed by pyrolysis reactions after short residence times of a few seconds only (Figure 2). Core technology is a twin screw reactor facilitating rapid heating up and intense contacting of the comminuted biomass at 500°C with a 10-fold excess of sand as heat carrier.⁶ The sand is separated, recycled, and reheated by hot flue gas in a pneumatic loop.⁵ Depending on the type of biomass, up to 60 wt% of liquids and around 20 wt% of solids (char and ash) and noncondensable product gas each are obtained; the latter can be used in the process for energy supply.⁶ By using ash-rich feedstocks, usually two condensates are obtained by a two-step condensation. As an average of the last test campaigns carried out with wheat straw as feedstock (containing ca. 6% of ash) around 34 wt% of organic condensate (containing ca. 10 wt% solids and a water content of ca. 15 wt%) were obtained, 25 wt% of aqueous condensate (containing around 80 wt% of water), as well as around 20 wt% of solids and pyrolysis gas each.⁷ The viscosity of the organic condensate after the first condensation step at 80–90°C is fairly below 100 mPa·s and by that is free flowing and well pumpable. At room temperature, the viscosity can rise up to ca. 500 mPa·s and even higher values. To maintain smooth handling and storage, the organic condensate is kept warm at ca. 40°C, where the dynamic viscosity is less than half of that value. The heating value of both the solids and the organic condensate is around 23 MJ/kg, while that of the

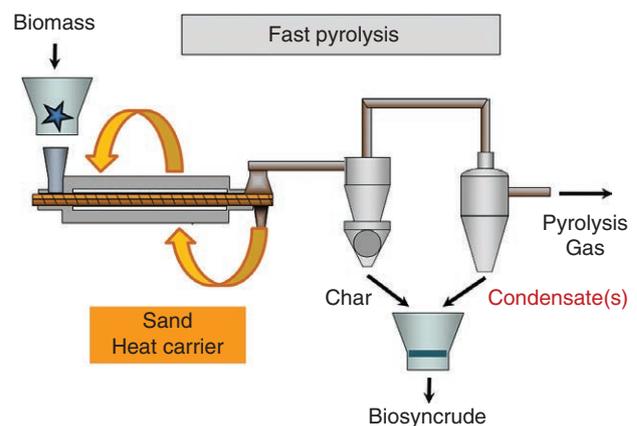


FIGURE 2 | Scheme of fast pyrolysis and biosyncrude production.

aqueous condensate is reduced to ca. 7 MJ/kg by the high water content.

Both condensates are intended for use as gasification fuels by suspending pyrolysis char with a colloidal mixer and milling system. In regard to complete use of the liquid and solid pyrolysis products, ca. 20 wt% char can be mixed to the organic condensate. To achieve a reasonable high heating value, the aqueous condensate can be loaded with up to 40 wt% of char with commercially available mixing technology.⁸ The bioslurries, also referred to as biosyncrude, have higher volumetric energy density than the baled straw and allow a compact handling, storage, and transport; without the risks connected with self-igniting char powder handling. At the bioliq pilot facility, the biosyncrude is prepared by colloidal mixing and stored in the tank farm prior to gasification. Industrial partner for the mixing technology is

MAT Mischanlagentechnik, Immenstadt. For further conditioning of gasification fuels, additional equipment such as in-line and batch milling devices are implemented in recycle loops prior to the tank farm. The fast pyrolysis plant has been designed for 2 MW thermal fuel capacity (ca. 500 kg/h) and is in full operation since 2010, partnered by Air Liquide, Frankfurt. So far, 15 test campaigns have been carried out for improvement and optimization trials. From wheat straw, ca. 80 t of pyrolysis products have been produced in 350 h of operation. In total, the sand heat carrier loop was operated more than 2000 h including stand-by operation and test operation for the heat carrier system only.

The 'central' part of the pilot plant schematically is shown in Figure 3. The slurry fed, oxygen, and steam blown 5 MW (1 t/h biosyncrude) high-pressure entrained flow gasifier has been designed for pressures up to 80 bar.⁹ The system is designed to utilize fuels with calorific values in the range from 13 to 25 MJ/kg. A twin fluid atomizer nozzle enables the conversion of fuels with high viscosity up to 1 Pa·s. The gasification chamber is equipped with a SiC lined, water cooled membrane wall particularly suited for the conversion of ash rich feedstock. This construction allows fast start-up and shut-down procedures. An example for a start-up procedure is shown in Figure 4. The downdraft gasifier flame reaches temperatures of 1200–1600°C well above the ash melting point. The molten slag drops into a water bath at the gasifier bottom for cooling and batch-wise removal by lock hoppers. At the gasification chamber exit, the hot raw syngas is quenched with a water spray and passes a water reservoir by a dip tube.

Different feedstocks have been utilized in several mixtures. As liquid phase ethylene glycol was used to prepare reference or model slurries; tar

condensate from bioliq straw pyrolysis as well as from wood pyrolysis purchased from Profagus, Germany, and BTG, Netherlands, were used. As solids straw char as well as charcoal from wood pyrolysis were used to prepare bio-slurries with up to 25 wt% char content; in addition, up to 5 wt% straw ash from straw combustion could be added to the charcoal mixtures. Beginning with the commissioning in 2013, up to now nine test campaigns have been carried out for improvement, balancing, and optimization. During nearly 300 h of operation with fuel, 230 t of model slurry, tar condensate, and biosyncrude were converted into syngas. Also for the gasification project launched in 2008, Air Liquide is industrial partner.

For validation of measurements and as prerequisite for the data evaluation mass balances are raised for carbon, hydrogen, oxygen, and nitrogen constantly at each test setting. In Table 1, an example for two different fuels used during a selected test campaign is given. Slurry 1 is ethylene glycol with 25 wt% charcoal and 5 wt% straw ash. Slurry 2 is wood-based pyrolysis oil with 5 wt% straw ash.

The syngas composition obtained in this campaign varied depending on the oxygen/fuel ratio and on reactor temperature. On a water free basis, the hydrogen content varied from 29 to 34 v%, that of CO varied from 31 to 39 v%, and CO₂ was found to range between 15.5 and 18.6 v%. Owing to the high reactor temperature, methane was not measurable. The cold gas efficiency of the gasifier was at maximum 67.7% in this campaign. For the relatively small reactor volume and an ash melting temperature of up to 1210°C, this can be considered a good efficiency.¹⁰ One development target is to reduce ash melting temperatures by the use of fluxing agents, which will lead to lower gasification temperatures and, accordingly, higher cold gas efficiencies.

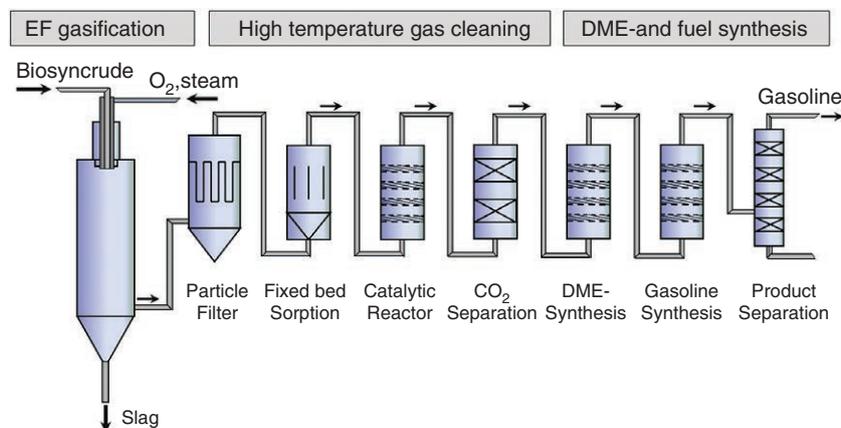


FIGURE 3 | Scheme of the gasification, gas clearing, and synthesis train.

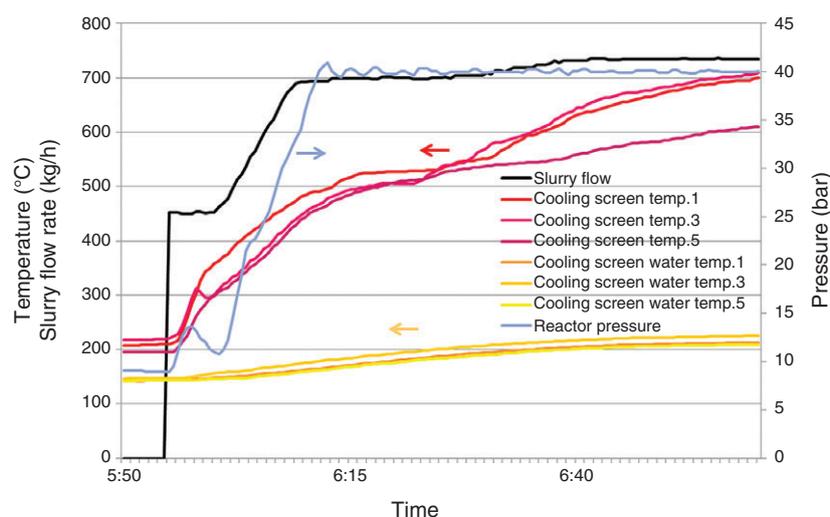


FIGURE 4 | Start-up procedure of the high-pressure entrained flow gasifier.

TABLE 1 | Composition and heating value of two selected bioslurries

Slurry	C wt%	H wt%	H ₂ O wt%	Ash wt%	HHV MJ/kg
1	57.4	6.4	3.9	5.0	23.6
2	45.3	7.9	1.9	5.0	20.7

The last project completing the bioliq pilot plant was on syngas cleaning and fuel synthesis realized from 2009 to 2011. Hot syngas cleaning techniques at system pressure up to 80 bar developed at KIT remove the various catalyst poisons and undesired gas components, complemented by a conventional Selexol scrubber for CO₂ separation.¹¹ The clean syngas target levels, which must be achieved for all contaminants, are extremely challenging and they must throughout fall below 0.1 ppmv. In hot syngas cleaning, at temperatures between 700 and 800°C, particulates are removed by ceramic filter elements. Acid gas components (HCl, H₂S, and COS) are retained by fixed bed sorption with alkali and earth alkali-based sorbents at temperatures ranging from 500 to 800°C. Contaminants level of H₂S and COS are much below the specified targeted levels. A visible breakthrough was caused by a design failure in one of the sorption beds and induced a shutdown in the test run. Ammonia, cyanides, and other small organic and heteroatom containing compounds are catalytically decomposed in the same temperature range as the fixed bed sorption. Depending on the process temperature, Pt- and Ni-based catalyst are applied at 500 and 800°C, respectively. MUT Advanced Heating, Jena, is industrial partner for this part of the bioliq plant.

The fuel synthesis pathway selected for the bioliq pilot plant proceeds through DME production in a first stage.¹² By a mixed Cu/Al₂O₃ catalyst, methanol is formed from syngas and subsequently following dehydrated to DME; also the water gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2 + \text{CO}_2$) is facilitated, leading to the overall reaction equation $3 \text{CO} + 3 \text{H}_2 \rightleftharpoons \text{CH}_3\text{OCH}_3 + \text{CO}_2$. Compared to methanol, DME has the advantage of a higher equilibrium yield, favored at lower H₂/CO ratios of about one, typically obtained by biomass gasification. In the next step, gasoline rich in aromatic compounds is produced by a zeolite ZSM 5 catalyst. Hydrocarbon yield and gasoline quality achieved are in accordance with those reported for the original Exxon Mobil Methanol-to-gasoline process.¹³ About 40% of gasoline and around 5% of liquefied petroleum gas (LPG) and some light gas besides 56% of water are produced.¹⁴ Depending on reactor type and operation conditions, a typical hydrocarbon composition consists of up to 55 wt% paraffins, 33 wt% aromatics, and of up to around 10 wt% of olefins and naphthenes each. Industrial partner for this part is Chemieanlagenbau Chemnitz. Inside the reactors, the fixed catalyst beds are segmented vertically by heat carrier containing plates connected to a kind of heat pipe system enabling efficient heat recovery for process steam generation. Full operation of the gasification-syngas cleaning-synthesis train has been achieved in 2014 for the first time by two test campaigns in June/July and in November. During the test runs, a few hundred liters of synthetic gasoline have been produced. However, the main objective of this first plant action was on technical and operational issues, not that much on fuel yield and quality.

The construction and erection of the bioliq pilot plant was facilitated by substantial funding. Of 64 Mio. EUR investment costs, the Germany, Ministry for Food and Agriculture along with Agency for Renewable Resources, FNR funded ca. 30 Mio. EUR, the state Baden-Württemberg, partly by use of EU EFRE funds, ca. 2 Mio. EUR. The Helmholtz Association of large research institutions in Germany, KIT belongs to, supported the plant construction with ca. 5.4 Mio. EUR. The partners from industry contributed to one quarter of the investment. For operation and maintenance, costs are assumed in the order of ca. 5% of investment costs. Following the construction phase, cooperation and license agreements were concluded with the industrial partners mentioned above. With these companies, the pilot plant is jointly operated and further developed to technical maturity. To run the pilot plant the envisaged ca. 1000 h per year, a technical staff of 45 engineers and operators of mainly mechanics and electricians is available. From the institutes participating in the project, additional staff is detached during plant operation for technical, scientific, and analytical support.

R&D FRAMEWORK

The pilot plant aims at demonstration the bioliq technology on a TRL level of 6. Reliable mass and energy balances will be provided; practical experience in operation and on equipment used will be gained. Furthermore, fuel flexibility and product quality have to be verified. Also, the bioliq pilot plant acts as a research platform which is embedded in a broad R&D framework, forming the basis for a knowledge-based optimization and further development of the technical processes, also allowing to explore applications of the products and technologies involved. A PhD student network exists, currently consisting of ca. 25 graduate students working on different scientific aspects of the bioliq value chain (complete list with research topics see www.bioliq.de). As an example the influence of pressure on gasification, syngas cleaning and synthesis issues has been investigated.¹⁵ For detailed studies on specific aspects, process development units in kg-scale, test facilities, and lab-scale plants for parameter studies and for the determination of materials as well as reaction and process data are in use. The virtual institute HVIGasTech, funded by Helmholtz Association, provides an excellent platform for scientific collaboration of currently nine research partners on the modeling and simulation of oxygen blown, high-

pressure gasification of liquid and particle-loaded slurry fuels in an entrained flow reactor (<http://www.hvigastech.org/>).

SYSTEMS ANALYSIS

From the very begin, the bioliq project was accompanied by techno- and socioeconomic as well as by life cycle assessment conducted by KIT authors but also by other institutions. In the most recent study, F. Trippe estimated the costs of syngas production by the bioliq process at 40 and 80 bar as well as those of DME-to-gasoline and Fischer-Tropsch synthesis.¹⁶⁻¹⁸ The production costs are based on biomass feedstock costs of 71€ per dry ton of wheat straw in average for the 20 years of plant life time. For 30 t/h gasoline production costs of 1.18 and 1.15 EUR/L are estimated in case of 40 and 80 bar gasification, respectively, while those for Fischer-Tropsch fuels have been estimated to 1.26 and 1.23 EUR/kg. Energy efficiencies for hydrocarbon production vary between 38 and 39%. The higher absolute capital costs in the Fischer-Tropsch synthesis concept are partly compensated by the higher fuel production. The slight advantages of the DME synthesis concept cases are caused by higher electricity revenues.

In a number of studies, production costs of syngas have been investigated.¹⁹ The different plant configurations according to the decentralized/central bioliq concept can be compared by regarding the Fischer-Tropsch synthesis with significantly varying gasification capacities between 200 and 4000 MW_{th}. Based on straw as reference feedstock, the efficiencies related to the energy content recovered in the fuel product is in the range of 38 ± 5% for all studies. A reasonable effect on economy of scale can be observed as shown in Figure 5. With an obvious scattering, specific production costs from 0.80 to 1.90 EUR/L fuel are found. Apparently, there is a strong demand for reliable process and material input data and transparent, harmonized cost models suitable for comparative studies. Regarding the process efficiency, it is important to understand that heat and electrical power are inevitable side products, by which the process energy demand can be satisfied.¹² Therefore, high CO₂ reduction potential can be achieved by the overall process chains.

Also, studies on the available, sustainable mass potential have been performed regularly in cooperation with partners. In the recently finished BioBoost EU FP 7 project (www.bioboost.eu), the availability of residual types of biomass along with their prices and supply curves has been studied in detail. With

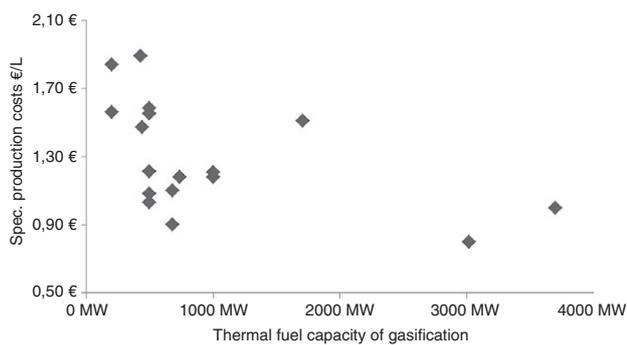


FIGURE 5 | Specific production costs in dependence of production scale by different authors.

high spatial resolution on regional NUTS 3 level straw was identified with the highest potential with ca. 150 Mt resulting in a mass share of 37% of all regarded biomass residues and exhibiting 48% of their energy content. The second largest potential of ca. 118 Mt can be generated from forestry residues (29%, both in terms of mass share and energy content). The results are available in a public Geoportal (iung.neogis.pl/geoportal/). Also the data have been applied to a heuristic simulation model, developed to optimize the (1) logistics of biomass supply, (2) conversion into intermediate energy carriers by fast pyrolysis, catalytic pyrolysis, or hydrothermal carbonization, and (3) their application for heat, electrical power, and fuels production. By the BioBoost Navigator simulation tool developed (also online available as on the project home page), locations for most economic sites of the conversion plants can be determined for different types and quantities of biomass by optimizing biomass supply regions, transportation distances through real traffic lines, and conversion plant location and size. The evaluation of such scenarios is helpful for process development and business case studies within decentralized/central concepts like the bioliq process. As an example for an EU wide bioliq implementation a scenario was set up, in which 52 Mt of straw, meaning an average utilization share of 35% per region are utilized by the process. This results in the production of 5.5 Mt of biofuel per year. The regions with the highest straw production can be found in France, Spain, and in the East of Europe in general. As the optimum simulation solution 137 fast pyrolysis plants have to be constructed, the capacities of which vary within a few 10^5 t/a. Approximately 10 times less central plants are built with correspondingly 5–10 times larger conversion capacities when compared to the fast pyrolysis plants. This supports the decentralized/central principle, where an intermediate is locally

produced and centrally converted. Assessing the profitability, the regions with the lowest production costs were found to be in Hungary, Poland, and Romania.

CONCLUSION

After successful commissioning of the pilot plant in 2014, the focus of plant operation now is on increasing the plant availability, process, and product optimization. Optimization of the fast pyrolysis plant, verification of fuel flexibility, and implementation of a fuel conditioning strategy for most efficient gasification is in development for wheat straw as a biomass representative for ash rich feedstocks. Now, pyrolysis products have to be produced in quantities sufficient for gasification and conversion into synfuels at the pilot plant. Next miscanthus as a purpose grown energy plant and wood are planned to be utilized. The reason for using the latter is not so much on the bioliq concept, but to allow for comparison with other processes mainly based on wood.

In gasification, a main issue is fuel flexibility, particularly in regard to changing composition in inorganic components. This is important in regard to slag formation and behavior, but also for burner design and operation. The high temperature line in the gasification-synthesis-train is not complete in the first, actual development stage of the pilot plant. Hot gas abstraction from the gasifier at around 800°C as well as high temperature CO_2 separation step by a hydrotalcite membrane process currently under development¹⁵ have to be realized in a next pilot plant expansion phase.

The gasoline obtained by the currently used, commercially available catalysts is a fuel of high octane numbers thanks to the high content of aromatics. For blending according to the German biofuels quota act (5% mandatory), it could foreseeable be used without further modification. However, superior quality of a synthetic biofuel taking advantage of the synthesis chemistry is a must, when economic performance should be attained. As an example, polyoxymethylene ethers (OME) are known to be excellent components, e.g., in diesel fuel. Their use is particularly attractive because of their high oxygen content, which prevents the formation of particulate pollutants already at the combustion stage. Thus, an elaborate exhaust gas treatment and engine-related modification of combustion parameters can become unnecessary. If the OME are produced from renewables, e.g., via methanol or dimethyl ether, they contribute not only to a reduction of harmful emissions but also to a reduction of CO_2 emissions in a double beneficial

way. Furthermore, the originally included oxygen can remain to a large extent in the product so that a synthesis with high energy efficiency and carbon economy is possible compared to pure hydrocarbon fuels. However, commercial production on a technical scale is not established since there is still lack of an efficient process, which meets economic and ecological demands. This and other high performance fuel options are investigated on the Synthetic Fuel Development Platform to be established with partners from car and engine producers, oil companies and fuel testing institutions. R&D activities range from fundamental challenges like the development of highly active and stable catalysts, to technical topics, such as reaction engineering, scale-up, and product testing in combustion engines. Another important issue is process integration into existing

industries and infrastructure, cofeeding of fossil feedstocks (to potentially improve economics) and external hydrogen supply to maximize carbon efficiency and thus product yield.²⁰

Synthetic biofuels can hardly be economic today. However, they provide excellent CO₂ reduction potentials (at least 82% from biomass to fuel production according to the studies performed in the BioBoost project), ecological and environmental performance when produced from biogenic residues. Therefore, the use of biomass as the only renewable carbon carrier for chemistry and energy carrier production on a long term will remain a challenging task. For this type of mid- to long-term research and development, pilot plant operations in combination with a consistent R&D platform are inevitable tools for long-term, science-based process development.

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