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Evaluation of Techno-Economic Studies on the bioliq® Process for Synthetic Fuels Production from Biomass

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Abstract: Techno-economic studies by various research institutions on the costs for the production of biomass to liquid (BtL) fuels using the bioliq® process were analyzed and evaluated. The bioliq® process consists of decentralized pretreatment by fast pyrolysis plants for biomass energy densification, and of a central gasification and synthesis step for synthesis of gas and synthetic fuel production. For comparison, specific material and energy flows were worked out for both process steps, and conversion efficiencies were calculated for the conversion of straw to diesel fuel via the Fischer-Tropsch synthesis. A significant variation of the overall process efficiency in the range of 33–46% was mainly a result of the different assumptions made for electricity generation at the central location. After breaking down the individual cost items to either fixed or variable costs, it turned out that the largest cost items in the production of BtL fuels were attributable to feedstock and capital costs. Comparison of the specific investments showed that, in addition to economies of scale, other factors had a significant influence leading to values between 1000 and 5000 EUR/kW. This, particularly, included the origin of the equipment purchase costs and the factors applied to them. Fuel production costs were found to range between 0.8 and 2.6 EUR/L. Possible cost reduction by learning potential was investigated, leading to an improvement by a few percent of production costs. A sensitivity analysis of the individual cost items by up to 30%, for "investments" and "biomass and transport" cost increases, led to higher manufacturing costs of up to 17% in both cases. By harmonizing the depreciation period and the chosen interest rate, the production costs changed from −16% to +17%. Similarly, effects could be shown by adjusting the costs for maintenance and servicing, and the plant operation time. A superposition of these effects in a best-case scenario led to cost reductions of 21%. The most expensive variant in the opposing worst-case scenario raised costs by up to 27%. This uncertainty contributed already fifty percent to a preliminary cost estimate based on a conceptual design.

Keywords: technoeconomic evaluation; bioliq® process; biomass-to-liquids; efficiency; production cost

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1. Introduction

Biomass-to-liquid (BtL) processes for the production of synthetic fuels are relatively recent technologies that are still under development. In these processes, lignocellulosic biomass, organic residues and waste are converted by thermochemical processes into synthesis gas, which is catalytically reacted to form different types of synthetic fuels as the main products [1–4]. Compared to the commercially established gas-to-liquids and coal-to-liquid processes, the challenges for BtL development address mostly to the upstream part, converting a variety of biomass feedstock to clean syngas considering the specifics of feedstock availability and supply. These fuels produced are similar to those in use today, and it is expected that they can replace a part of the fossil fuels required for existing vehicle fleets in the short term. Easier adjustment to new developments in internal combustion engines and compliance with new regulations are expected as a result of modified processes or new synthetic products. Essentially, many different carbon sources may be converted into syngas mixtures of carbon monoxide, hydrogen and methane. Purpose-grown biomass, biomass by-products from agriculture, forestry and food processing, as well as organic waste (including plastics) can be used with different technology pathways and process configurations. Also, carbon dioxide together with hydrogen, produced from electrolysis of water using renewable electrical power, can be converted into syngas and to synthetic fuels (PtL, power-to-liquids). Even a combination of BtL and PtL is possible, making use of the CO_2 by-produced in thermochemical processes. Thus, nearly complete use of the feedstock carbon in synthetic processes is possible [5]. The potential of sustainable biomass residues is limited, and its use for bioenergy is subject to controversial discussion. However, synthetic BtL fuels may have significant potential as renewable fuels for early implementation on the way to defossilized transportation.

The development of BtL processes has advanced significantly in the last decades. Commercial application has failed, so far, because of missing competitiveness to conventional fuels. In Table 1, a selection of pilot and demonstration plants with Technology Readiness Levels (TRL) between 6 and 8 for the conversion of lignocellulosic biomass into different types of synthetic fuels via gasification pathways are listed, providing evidence as to the range of technologies, conversion capacities and state of development. Due to the importance of Scandinavian wood industries, the earliest efforts can be observed in this region. Many more examples of synthesis gas trains are given in the global database of biomass conversion facilities of IEA Bioenergy (www.ieabioenergy.com/installations, accessed on 12 April 2021), including advanced biofuels, combustion, gasification and pyrolysis plants. The examples given in the table show the multitude of options to set up a process chain regarding feedstock, pretreatment, gasification and synthesis technology.

In recent years, therefore, a large number of studies and reports of the various process developers and researchers relating to BtL, and other advanced biofuel production processes, have emerged. In addition to the possible advances of the various novel technology approaches for processing biomass, entire process chains with their economic and environmental aspects have been assessed [6–9]. These studies include various gasification-based fuels derived from chemical-catalytic and biocatalytic syngas conversion as well as products from pyrolytic and solvolytic processes, which are catalytically upgraded directly to fuels or to intermediates for refinery coprocessing. Technoeconomic studies are a valuable tool to estimate the economic performance of a process in the early state of its development and to compare it to established processes and products, as well as to alternative developments. A number of comparative studies on alternative BtL pathways exist. They mainly differ in gasification technology and syngas product. Stahlschmidt in 2010 compared different technologies for the production of methanol, one and two-step production of dimethyl ether, as well as of gasoline, Fischer-Tropsch hydrocarbons, and SNG (substitute natural gas) products [10]. Based on AspenPlus simulations for a gasifier with a thermal fuel capacity of 200 MW, the overall conversion efficiencies varied between 18.4 and 65.5% with specific production costs ranging between 15.5 and 40.6 ctEUR/kWh. The most sensitive parameter were the fuel supply costs. The technoeconomic evaluation by Dimitriou et al., in particular, examined and quantified the effect of uncertainty of key parameters on the fuel production costs when using Monte Carlo methods [7]. Production costs were found to be within 6.4–9.1 ctEUR/kWh of produced fuel. Interestingly, the uncertainty analysis indicated that deterministic estimates or sensitivity analyses of production costs may systematically underestimate the production cost of biofuels, as they do not account for the effect of simultaneous variations of parameters. Considering this effect, one of the six investigated scenarios even turned out to be economic within a certain probability.

Table 1. Selected pilot or demo projects for biomass to liquid (BtL) processes.

No.	Project	Feedstock	Key Technologies	Products
A	LTU Green Fuels, S	Black liquor, pyrolysis oil	Chemrec process with EFG, 2 MW, 30 bar, 4 t/d production	DME, methanol
B	Güssing Renewable Energy Multifuel Gasification, A	Forest biomass and others	Repotec fast internally circulating fluidized bed (FICFB), 8 MW, atm. pressure	CHP, SNG (1 MW), FT plant (slip stream)
C	NSE Biofuels Oy, Varkaus, S	Forest biomass	CFB, 12 MW Foster Wheeler, hot filtration, catalytic tar reforming, (5 MW for synfuel application)	Heat for a lime kiln, FT-products (slip stream)
D	bioliq®, KIT, D	Lignocellulose bio-slurries	Fast pyrolysis 2 MW + 5 MW entrained flow gasification, hot gas cleaning, 80 bar	MeOH/DME, gasoline
E	Goteborg Energie AB, GoBiGas, S	Forest biomass	metso/repotec Dual bed, 20 MW (50.000 t/y SNG)	Biomethane
F	Total, BioTfuel demo, F	Forest biomass	Torrefaction + Uhde Prenflow EF, 15 MW, 8000 t/d FT product	FT-products
G	Värmlandsmetanol, S	Forest biomass	Uhde-HTW gasifier, 111 MW	Methanol
H	Växjö Värnamo Biomass Gasification Centre, S	Forest biomass	Foster Wheeler pressurized CFB + hot gas filtering	Heat & power, clean syngas
I	Woodland Biomass Research Center, LLC Thermal Reformer Synthesis West BiofuelsWoodland, CA	Forest biomass	Dual fluidized bed gasifier, 5 t/d waste wood,	FT products
J	Red Rock Biofuels, Oregon, US	Forest biomass	Gasification, 44.0000 t/y FT liquids	FT products

The influence of plant size and constellation was also investigated. Regarding biomass, economies of scale always compete with biomass transportation costs, i.e., economies of logistics, which consequently lead to an optimum in the specific production cost vs. conversion capacity curve for biomass conversion plants [11]. To avoid long transportation distances, particularly for biomass with low energy density, decentralized pretreatment plants could be located in regions with large feedstock potentials. The so-produced intermediate energy carriers are more transport-worthy concerning their energy density and handling, enabling cheaper transport over long distances to a central plant for efficient further conversion and upgrading to desired transportation fuel. Depending on the desired conversion capacities, type of feedstock and supply chain, different pretreatment processes may be recommended with increasing draw areas to provide low feedstock supply costs. This was, for example, validated in simulations utilizing forest materials and switch grass both by thermochemical and mechanical pretreatment in North American regions [9,12]. In addition, mixed feedstock would provide further potential of reduced supply costs [13,14]. Dedicated studies on the effect of conversion capacity on the productions costs of BtL fuels were also conducted e.g., by R. Stahlschmidt et al. [10] or by L. Leible in [15], who investigated biomass residue potential in one of the federal states in Germany and derived and compared different plant configurations and sizes. In the FP7 BioBoost project, optimized production costs of a plant network of decentralized fast pyrolysis (FP) and central gasification/synthesis plants were calculated including a model for biomass logistics [16]. The EU-wide simulation of the FP pathway implementation showed a straw utilization of 52 Mt/a for biofuel production, meaning an average utilization share per region of 35%. This resulted in the production of 5.5 Mt of biofuel per year. The regions with the highest straw production were found in France, Spain and in the East of Europe. In the optimum simulation scenario, 137 straw FP plants were erected, the capacities of which varied between "small" (<200,000 t/a) and "very large" (>350,000 t/a). Approximately 10 times less biosyncrude plants were utilized with correspondingly 5–10 times larger conversion capacities when compared to the FP plants. These results confirm the possible benefits of the local-central principle, where an intermediate is locally produced and centrally converted to final products. Gunukula et al. investigated the effect of different pretreatment technologies for biomass densification by pelletization and torrefaction, including the necessary grinding and drying steps, for both wood and switch grass prior to FP with further upgrade to hydrocarbon fuels by hydrotreating [17]. The 500 t/d pretreatment plants each supplied a four-times larger fast pyrolysis plant. Generally, minimum fuel selling prices increased when thermochemical pretreatment was implemented. The most sensitive parameter was the product yield, making it obvious that, in the case of fast pyrolysis, not only bio-oil but also the char product should be utilized for fuel production within a gasification pathway. This was confirmed in the study of Brown et al. [18] where biofuel production via pyrolysis bio-oil/char slurry showed better performance than only the use of bio-oil. In that study, woody material was processed in mobile pretreatment units, further reducing biomass transportation costs. Optimum conversion capacities were found in the range of 2250–2750 t/d, for which specific production costs of 1.68, 1.55 and 1.35 EUR/L were estimated to convert bio-oil, bioslurry and torrefied wood into Fischer-Tropsch fuels. Alternative to the gasification pathway, bio-oil may also processed to fuels or fuel components by conversion via catalytic deoxygenation, hydrogenation, cracking and related reactions. Here, TRL is less than that of BtL processes today and early-stage technoeconomic evaluations reveal specific production costs in the same range as for BtL fuels, either as stand-alone plants or in coprocessing in a refinery. Instead of using the solid pyrolysis product for heat generation, it may be utilized for hydrogen production in self-sustaining stand-alone plant concepts [19–21].

However, as most of the BtL processes are still in the pilot or demo phase (TRL 6-8), and not much experience from a large-scale industrial plant is available for the key technologies, these studies are based on numerous assumptions to enable calculation of the specific cost of fuel production. That way, differences and uncertainties in selection and pricing of equipment, estimation of the material and energy flows, as well as the economic model and parameters, may occur. Consequently, this means that divergent results may be obtained if the economic performance of a process is investigated by different investigators. Therefore, in this work, different studies on the same process were conducted in order to evaluate the type, extension and sensitivity of uncertainties which may arise using the example of the bioliq® process developed at KIT. This particular process appeared as a useful example, because it was examined in several studies. Since nearly all of them made use of the same technical information, it could be expected that differences in the estimated production costs were mainly due to cost estimates and economic factors. With one exception, biomass logistics were not taken into account, reducing complexity for upstream costing by simply assuming feedstock costs at the plant gate. From the results obtained in this study, it was expected that they could be transferred to other process developments and some general conclusions may, therefore, be drawn in view of more reliable technoeconomic evaluations. For the bioliq® process, fuel production costs (minimum selling price) between 0.80 and 2.50 EUR/L could be found (for comparison: 1 L diesel fuel is equivalent to 10.0 kWh or 36.0 MJ). This range of calculated production costs per liter of fuel does not allow a direct comparison of the cost-effectiveness of the different process constellations, and the question arises how the results are influenced by plant size as well as technical and economic parameters. At the same time, nontransparency of the procedure and a lack of information prevented a simple follow-up of the studies. To elaborate in detail the premises and methodology used in the studies, the material and energy flows as well as method and parameters of production cost estimates in dependence on conversion capacity were determined. A sensitivity analysis was carried out to evaluate the impact of different economic parameters on the assessment results. Finally, a harmonized set of economic parameters was applied to the different process configurations in order to compare the different evaluations of the bioliq® method on a common basis, achieving direct comparability among the studies.

2. Methods

For more than 15 years, research has been carried out on the development of a sustainable process for the production of second-generation synthetic fuels from biomass using the bioliq® process of the Karlsruhe Institute of Technology (KIT) [11]. Biogenic residues, such as straw or residual forest wood, were used as raw materials for this process. Agricultural biomass needs to be sourced from particularly large areas, and its transport may be unfavorable for the supply of large-scale plants. According to the bioliq® concept, biomass is converted into an energy-dense liquid-like product for easier and cheaper transportation by decentralized fast pyrolysis plants. From a number of such plants, the intermediate bioenergy slurry, consisting of liquid fast pyrolysis oil and char containing solid, also referred to as biosyncrude, would be collected and further convertsted in a large, central gasification and synthesis plant profiting from economies of scale. Due to this combination of local and centralized conversion plants, more favorable economic and environmental performance was expected for certain types of biomass. Another advantage of upstream pyrolysis is the homogeneity of the slurry. Its formulation enables the material properties to remain constant within a certain range of specifications, and it can be implemented more easily in the subsequent gasification process.

In the following, first the original concept of the bioliq® process is described. However, in the technoeconomic studies evaluated here, certain deviations from this concept have been made [22]. Then, the methodology for comparison of the studies is explained.

The first process step for the production of synthetic fuel according to the bioliq® concept is the pyrolysis of the biomass [10] as depiced in Figure 1. The air-dry biomass is initially shredded and then delivered to the reactor, where it is reacted within a few seconds of gas retention time at approx. 500 °C in an anoxic atmosphere. Rapid heating is provided by mixing the biomass particulates with an excess of hot sand in a continuously operated twin screw reactor. The resulting hot pyrolysis vapors and main fraction of solid char product are separated in a hot gas cyclone. Instant quench condensation causes a condensate rich in organics to condensate first (fast pyrolysis bio-oil), and an aqueous condensate is obtained in a second condensation step. The pyrolysis bio-oil and the char containing solid formed during the pyrolysis then form the slurry. The high yield of liquid condensates is a prerequisite for the production of slurries with desirable material properties, such as particle size distribution, viscosity, and heating value. The production of biosyncrude suitable for gasification was investigated at KIT and still requires further research and development [13]. In the technoeconomic studies considered in this meta-analysis, biosyncrude was always considered as the sum of liquid condensates and solid char product without specifying its fuel characteristics, except for the heating value. The noncondensable gas, mainly consisting of CO and CO_2, can be used as process energy to reheat the sand as heat carrier medium.

Another central element of the bioliq® process is the gasification process, based on the Lurgi Multi-Purpose-Gasification (MPG) concept [14]. The biomass-based slurries from pyrolysis are gasified with pure oxygen in a high-pressure entrained flow gasifier at temperatures above 1200 °C and a pressure of up to 80 bar. The high temperatures ensure almost complete carbon conversion. The reaction chamber of the gasifier is surrounded by a water-cooled membrane wall, on which a protective layer of a centimeter-thick slag layer is formed. This prevents possible erosion and corrosion processes. At temperatures above the melting point of the ash, all inorganic material recovered from the gasifier is as a liquid slag by a lock hopper system. In the bioliq® concept, cleaning and conditioning of the syngas obtained is performed by high-temperature, high pressure gas cleaning after hot gas extraction from the gasifier. This helps to avoid heat losses and the installation of blowers that compress the synthesis gas to the pressure required for the synthesis. The high pressure ensures a rapid carbon conversion with relatively low oxygen consumption and a short residence time.

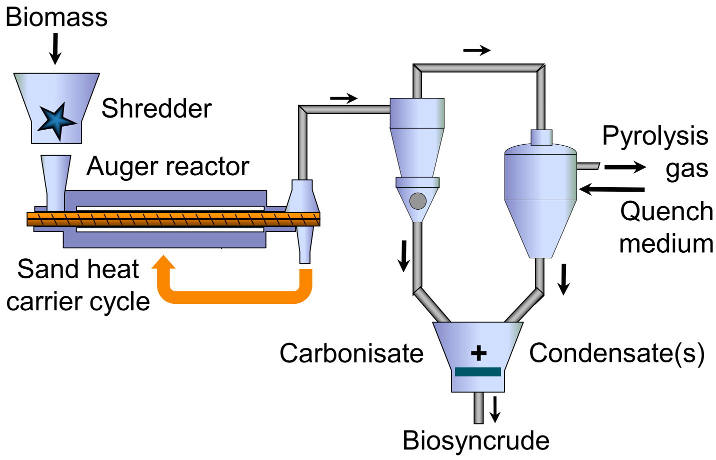


Figure 1. Schematic of the de-centralized fast pyrolysis process.

Due to the high reaction temperature, a tar-free synthesis gas (with a very low methane content below 1 vol.%) is formed. The dry gas mainly consists of carbon monoxide (CO) and hydrogen (H_2) (approx. a 1:1 ratio) as well as carbon dioxide (CO_2). Sour gases like CO_2, HCl, and H_2S, as well as small amounts of other impurities such as ammonia (NH_3), cyanide (HCN), and carbonyl sulfide (COS), are removed in the subsequent gas cleaning process up to the required limit value [15]. Once clean syngas is obtained, a variety of processes can be added to produce any type of hydrocarbon fuel (gasoline, diesel, jet fuel), oxygenate products (methanol (MeOH, dimethyl ether (DME)), and also hydrogen and methane (SNG, substitute natural gas).

The bioliq® pilot plant that as shown schematically in Figure 2 is operated at KIT along the whole process chain since 2014 differs from the original concept to a certain extent [22]. For syngas use, gasoline type of fuel is produced after single reactor MeOH/DME synthesis.

Nine studies on the bioliq® process, which were performed by different institutions within eight years from 2006 to 2014, were evaluated, and are compiled in Table 2. In principle, they consist of two groups of studies. First, technoeconomic evaluations were performed within dissertations at KIT dedicated to the investigation of the bioliq® concept, evaluating the production costs utilizing different feedstock and products. The second group consisted of studies performed on the comparison of different BtL pathways, including, but not exclusively dedicated to the bioliq® process. In all cases, the primary reports were used as data sources, which were mostly published in Germany. However, reviewed papers were also published in a number of cases. These are also given in the references.

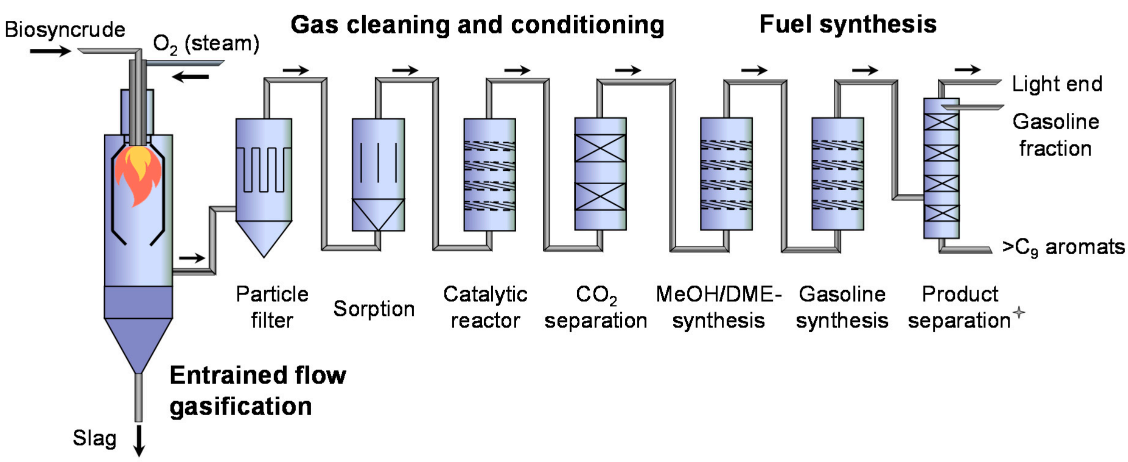


Figure 2. Schematic of the central part of the bioliq® concept.

Table 2. Overview on the techno-economic studies investigated in this work.

No.	Study	Type	Author	Institution	Year	Ref
1	Kraftstoff, Strom und Wärme aus Stroh und Waldrestholz—eine systemanalytische Untersuchung	Report	L. Leible et al.	Institut für Technikfolgenabschätzung und Systemanalyse (ITAS)—KIT	2007	[23]
2	Systemanalytische Untersuchung zur Schnellpyrolyse als Prozessschritt bei der Produktion von Synthesekraftstoffen aus Stroh und Waldrestholz	PhD thesis	S. Lange	Institut für Technikfolgenabschätzung und Systemanalyse (ITAS)—KIT	2008	[24]
3	Modellierung und Bewertung von Prozessketten zur Herstellung von Biokraftstoffen der zweiten Generation	PhD thesis	P. Kerdoncuff	Institut für Industriebetriebslehre und industrielle Produktion (IIP)—KIT	2008	[25]
4	Cost estimate for biosynfuel production via biosyncrude gasification	Report	E. Henrich et al.	Institut für Katalyseforschung und -technik (IKFT)—KIT	2009	[26]
5	Techno-ökonomische Bewertung alternativer Verfahrenskonfigurationen zur Herstellung von Biomass-to-Liquid (BtL) Kraftstoffen und Chemikalien	PhD thesis	F. Trippe	Institut für Industriebetriebslehre und industrielle Produktion (IIP)—KIT	2013	[27–29]
6	Biomass-to-Liquid“ BtL, eine Realisierungsstudie	Report	-	Deutsche Energie-Agentur GmbH	2006	[30]
7	Ermittlung spezifizierter Kosten und ökologischer Auswirkungen der Erzeugung von BtL Kraftstoffen und Biogas	Report	B. Meyer et al.	Institut für Energieverfahrenstechnik und Chemieingenieurwesen (IEC)—Technische Universität Freiberg	2009	[10,31]
8	Analyse von thermochemischen Konversionsverfahren zur Herstellung von BtL-Kraftstoffen	Report	D. Beiermann	Institut für Feuerungs- und Kraftwerkstechnik (IKF)—Universität Stuttgart	2010	[32]
9	Energy Carrier Chain LCA, Sustainability assessment of energy carriers	Report	Deliverable D6.4	EU FP7 BioBoost project	2014	[33]

Essential technical criteria taken into account were the plant configurations (number of pretreatment plants, conversion capacity of pretreatment and central plants), and the mass and energy input and output of local and central processing. In most cases, straw was selected as feedstock and Fischer-Tropsch (FT) hydrocarbons as the product. Straw was selected because it can be expected that the decentralized bioliq® concept is particularly suitable for ash-rich, low-energy types of biomass. FT synthesis was chosen because for this process it was found to be the most common synthesis process used in all the studies. That way, fuel production costs are related to one liter of diesel-like fuel with lower heating values ranging from 43.2 to 44.2 MJ/kg.

From the mass and energy flows, yields and conversion efficiencies were calculated, respectively. They are provided as the ratio of the energy contained in the product (either biosyncrude in the local or FT hydrocarbons in central processing plant) to the energy supplied to the process in form of feedstock, electricity and other fuels.

On the basis of these results, it was possible to examine the cost models for estimating investment and production costs. In the studies, missing information on parameters was calculated from given values, if possible, or queried directly by the authors. Each of the studies followed its own approach to calculating the different cost contributions and total costs. For a uniform treatment of the cost information with different degrees of detailing given in the studies, all expenses were allocated to "fixed costs" and "variable costs". Fixed costs are payments of a company that occur even when the plant is not in operation. They include capital costs (depreciation, interest, and construction costs), maintenance, repairs and servicing costs, insurance & tax payments, as well as personnel costs and overhead (administration, etc.). The annuity payments of the cost of capital are calculated using the following formula:

$$Annuity = I_0 \cdot \frac{(i+1)^n \cdot i}{(i+1)^n - 1} \quad (1)$$

with n: depreciation period, i: interest rate, I_0: total investment.

Variable costs are only incurred during the operation of the plant, and consist mainly of costs for raw materials, transport, operating resources and energy. Annual variable costs were calculated from feedstock cost (straw at gate of the local conversion sites) and transportation of biosyncrude. In cases where electricity was by-produced, revenues were included in the production cost estimate. Finally, the economic models for estimating production costs were related to their date of origin by a plant cost index, investigated in terms of learning effects as well as for sensitivity with regard to investment and biomass supply costs. Harmonization of the cost models made use of the highest values of economic parameters (worst case scenario) or lowest values of economic parameters (best-case scenario) includingthe percentages used to calculate capital cost and those for maintenance and repair, as well as plant operation time.

3. Results and Discussion

3.1. Mass and Energy Balance, Conversion Efficiency

First, the selected studies were analyzed with regard to their material and energy flows. The process chain for the production of BtL fuel was divided into its three main process steps. In addition to the fast pyrolysis process, the first process step, the local "pyrolysis," also includes biomass preparation, such as crushing and drying. The second, central part of the process is collectively referred to as "gasification and synthesis," and includes the process steps of slurry preparation, gasification and subsequent gas conditioning as well as the entire synthesis process including downstream product treatment as well as the energetic integration of residual gas and by-produced steam. This separation allowed for a modular analysis of the various studies and enabled comparison of the different approaches.

Table 3 provides a comprehensive overview of the numbers related to the material and energy flows in the various studies. For studies no. 2 and 5, adjustments became necessary because outputs of local and input of central sites were not consistent. The values of the input and output flows of the pyrolysis were then adjusted in both studies to the amount of biosyncrude required for gasification. The studies analyzed differed greatly in terms of their specified conversion capacity. While the smallest capacity only envisaged an annual biomass throughput of below 0.4 Mt, that of the largest assumed capacity of more than 9 Mt was roughly twenty times as much. Other studies mostly required biomass amounts between 1 and 2 Mt/a. Six of the nine studies used straw as biomass with a residual moisture of approx. 14 wt.% in their plant concepts. In Study 2, wood was used in addition to the straw and Study 6 did not denote a specific type of biomass, but only provided a calorific value and a moisture content of 30 wt.%, suggesting the use of wood as raw material. In one study, straw and wood were separately investigated as feedstock [10], and the resulting difference in the overall conversion efficiency along the whole process chain turned out to be only 0.5%.

Table 3. Overview of feedstock and process characteristics of the investigated studies.

Study	1	2	3	4	5	6	7	8	9
Biomass feedstock	Straw	Straw/wood	Straw	Straw	Straw	-	Straw	Straw	Straw
Water content/wt.%	14	14/35	15	15	15	30	14	15	15
Water content dry/wt.%	7	7	15	-	8	15	7	10	-
$LHV_{Biomass}$/MJ/kg	14.6	11.9	14.9	14.4	14.5	12.6	14.2	14.0	13.4
Decentralized pyrolysis plants									
Thermal fuel capacity per plant/MW	100	200	55	100	100	98	50	100	117
Number of plants	50	4	10	35	11	5	5	5	4
Total biomass conversion capacity/kt/a	9247	1785	1000	6944	1989	1000	413	1027	2190
Total biosyncrude capacity/kt/a	5902	1182	680	4618	1347	503	306	724	1480
$LHV_{Biosyncrude}$/MJ/kg	18.7	16.6	19.9	19.1	17.6	22.0	17.3	17.2	16.9
Conversion efficiency	82%	76%	85%	88%	78%	84%	72%	82%	84%
Central gasification + synthesis plant									
Biosyncrude conversion capacity/MW	4089	680	500	3056	941	439	200	425	999
Biosyncrude conversion capacity/kt/a	5902	1182	680	4618	1347	503	306	724	1480
Hydrocarbon product capacity/MW	1716	326	187	1500	375	186	115	207	404
Product capacity/kt/a	1069	201	115	1000	216	106	66	136	238
$LHV_{product}$/MJ/kg	43.32	43.83	43.90	43.20	43.86	44.05	44.15	44.00	42.8
Electricity export/MW	0	0	74	0	146	22	0	0	85.5
Conversion efficiency	42%	48%	37 + 22% [1]	40 + 22% [1]	42 + 11% [1]	43%	43%	48%	39.4 + 8.2% [1]
Overall energetic efficiency	34%	34%	34 + 14% [1]	43%	33 + 13% [1]	37 + 4% [1]	33%	39%	33.0 + 6.9% [1]

[1]: Related to fuel plus electricity production.

Table 3 contains the conversion efficiencies, also depicted in Figure 3. Those estimated for the local pyrolysis process varied between 72 and 88%. While comparatively high conversion losses occurred in studies 2, 5 and 7, the efficiency of the other studies was over 80%. Study 7 calculated the lowest efficiency, which was due to the high specific power consumption and the need for extra fuel. In Study 4, the consumption of electrical energy was not taken into account, as no value was given for it. This resulted in the highest efficiency of the pyrolysis process at 88%. The high efficiency in Study 6 can be explained by the above-average calorific value of the slurry, see Table 3. In all studies, Study 7 excluded, no additional fuel gas was required to heat-up and pyrolyze the biomass.

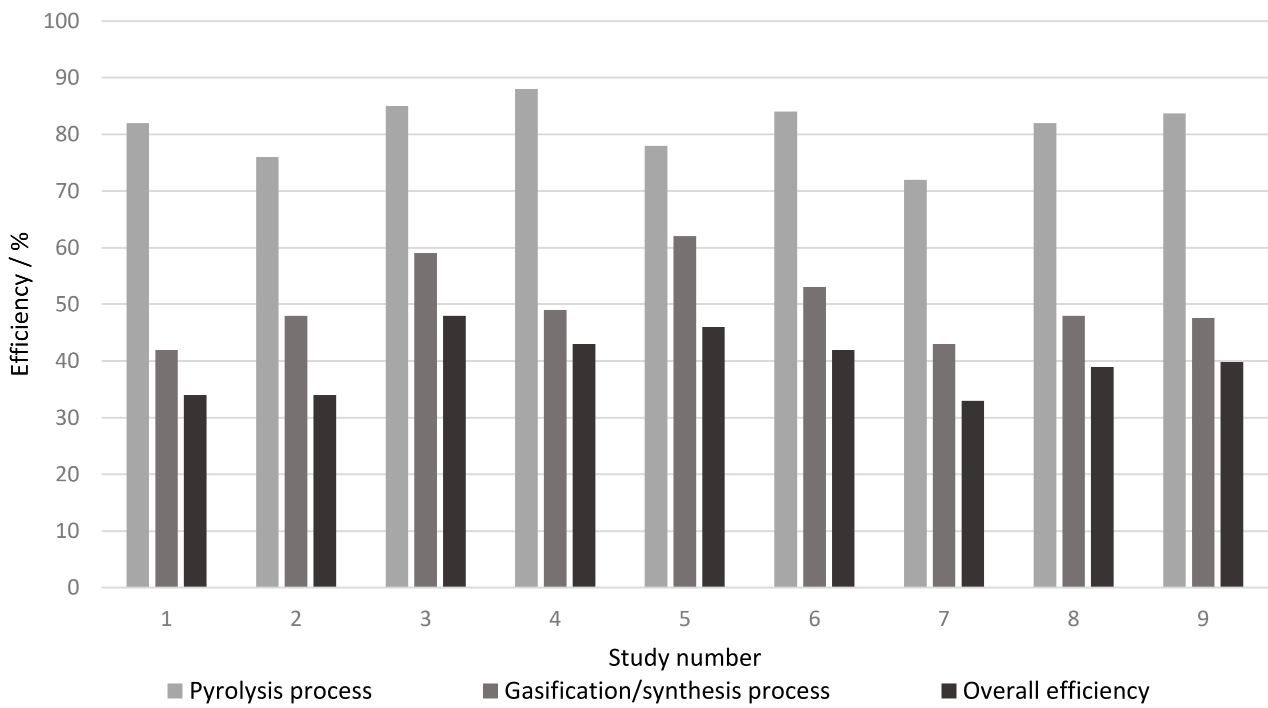


Figure 3. Conversion efficiencies of the local pyrolysis and the central gasification/synthesis processes together with those of the overall process in the investigated studies.

The amount of biosyncrude obtained from the biomass was, except of the higher value in Study 6, nearly the same across all studies, most likely because the authors made use of the same data published on the bioliq® process. It is interesting to see that notable differences in the composition of the biosyncrude occurred particularly with regard to the water content (Table 4). The water content of the dried biomass varied due to various assumptions for the intensity of the drying step and, consequently, differing amounts of water were found in the summed-up condensates. Surprisingly, the varying water content did not significantly affect the calorific value of the biosyncrude, which may be a consequence of the heating values assumed for its different components.

Table 4. Product yields by straw fast pyrolysis (data given in wt.%).

Study	**1**	**2**	**3**	**4**	**5**	**8**
Gas	23.10	18.30	20.00	21.40	24.80	21.20
Biosyncrude	76.90	81.70	80.00	78.60	75.20	78.80
thereof:						
Condensates	54.98	51.39	60.00	30.97	27.52	47.91
Char solid	21.92	23.86	20.00	29.79	24.97	21.83
Water		6.45	0.00	17.84	22.71	9.06
LHV/MJ·kg^{-1}	18.7	16.6	19.9	19.1	17.6	17.2

When looking for the conversion efficiencies of the central processing steps, significantly greater differences were found compared to those of the pyrolysis process. Deviations of up to 20% were seen between the studies. Comparatively high efficiencies were achieved in the studies no. 3, 5 and 6 that considered the by-production of electricity (see Table 3). In these studies, however, the energy content in the fuel was reduced. The high efficiency in Study 4 (49% even without electricity production) can be explained by the procedure used to estimate the efficiency, which was drawn up on the basis of purely stoichiometric considerations of the overall chemical reactions taking place. Thermal losses were also estimated, but were comparatively low A more detailed consideration of the differences was difficult because the data from the internal evaluation sheets or simulation models was not available.

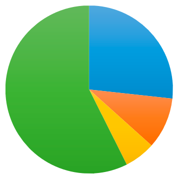
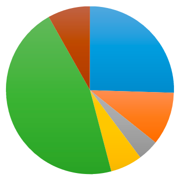
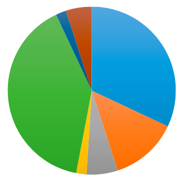
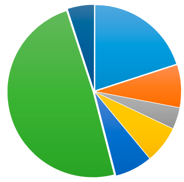
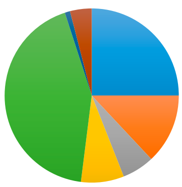
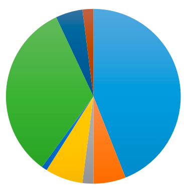
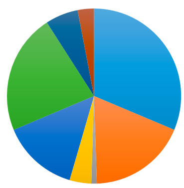
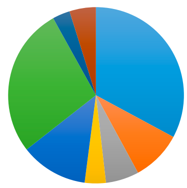
Regarding overall conversion efficiency, it is interesting to see that five out of the eight studies showed nearly identical efficiencies of 33% or 34% related to the hydrocarbon fuel production, only differing by whether or not electrical energy could be by-produced. The highest efficiency of 43% was again found in Study 4. There, the low thermal losses raised the efficiency to a comparatively high value. Based on the energy balance of the sole stoichiometric chemical reactions, a theoretical maximum conversion efficiency of around 55% can be assumed for the bioliq® process when pure oxygen is used for gasification. In average, the studies examined estimated an efficiency of 36% (± 3%) (leaving out Study 4) of the bioliq® process, based on the energy content of the fuel. This is a comparatively small deviation for an emerging technology, which, however, can be partially explained by the fact that the same sources were referred to. However, there were some significant differences between the studies in the assumption of electricity production. By-production of electricity was most relevant, particularly regarding the high gasification temperatures occurring and the possible heat use of several hundred degrees Celsius. In Study 5, the overall process was designed to be self-sufficient in terms of heat and electricity supply. Only excess amounts were exported into the electricity grid. The same was true for another studied carried out within the EU project RENEW, where around 45% conversion efficiency was estimated within a self-sufficient process [34]. Conversion efficiencies for the bioliq® concept appeared lower compared to those of other BtL technologies. In the IE study, efficiencies were reported to range between 40 and 55% [21]. Dimitriou et al. found 38 to 48% comparing different entrained flow and circulating fluid bed reactor technologies to produce Fischer-Tropsch hydrocarbon fuel from wood chips [7].

3.2. BtL Production Cost Estimation

3.2.1. BtL Production Costs

The allocation of the different cost contributions to fixed and variable costs enabled a fair comparison between the studies and clearly showed their distinguishing features. An analysis of the costs was not possible for Study 7 due to the lack of information on the total investment costs. Table 5 provides an overview on the cost models and contributions used in the investigated studies. Figure 4 displays the specific production costs determined per liter of hydrocarbon fuel and the associated contribution of fixed and variable costs. For Study 7 only the total production costs are shown. It can be seen that the specific production costs differed significantly both in total and in the distribution of fixed and variable costs. In total, the costs varied between 0.80 EUR/L and 2.37 EUR/L. In addition to the previously discussed conversion efficiencies estimated in the studies, this was also a result of differences in the methodology used to set up cost models. Any revenue from electricity production was deducted from the variable costs and thus their share was reduced. While fixed and variable costs made almost balanced contributions to the total production costs in studies 1, 2 and 4, the fixed costs were significantly higher in the other studies. In Study 9, costs incurred by research and development were also considered. However, there was a trend towards a decreasing proportion of fixed costs with increasing plant size, as could be expected.

Table 5. Economic parameters and cost contributions of the BtL cost evaluation; Colors of the pie chart: light blue: capital cost; orange: maintenance; grey: tax & insurance; yellow: personnel; blue: overhead; green: biomass; dark blue: materials; brown: utilities.

	Study 1	**Study 2**	**Study 3**	**Study 4**
Invest local plants	1,177,415 kEUR	341,598 kEUR	130,920 kEUR	700,000 kEUR
Invest central plant	2,011,136 kEUR	439,000 kEUR	401,490 kEUR	750,000 kEUR
Production costs	1.01 EUR/L	1.12 EUR/L	1.02 EUR/L	0.8 EUR/L
				
Capital cost	11.4% of TCI	9.4%	10.2%	14.2%
Interest rate	7%	7%	8%	7%
Depreciation period	18 years	20 years	20 years	10 years
Maintenance	4% of TCI	5/3% [1] of TCI	4% of TCI	6% of TCI
Biomass	72 EUR/t	68 EUR/t	63 EUR/t	64 EUR/t
Electrical energy price	-	61 EUR/MWh	76 EUR/MWh	-
Electricity demand	-	2.6 kW/L	1.9 kW/L	-
Share of electricity costs	-	0.06 EUR/L	0.05 EUR/L	-
Personnel	1287	306	50	1168
Annual operation time	7500 h	7500/8000 h	7502 h	8000 h
	Study 5	**Study 6**	**Study 8**	**Study 9**
Invest local plants	374,880 kEUR	245,160 kEUR	343,295 kEUR	640,722 kEUR
Invest central plant	693,200 kEUR	414,440 kEUR	691,526 kEUR	864,734 kEUR
Production costs	1.20 EUR/L	1.45 EUR/L	1.90 EUR/L	2.57 EUR/L
				
Capital cost	8.3% of TCI	13.6%	10.2%	9.3%
Interest rate	5%	8%	Not specified	5%
Depreciation period	20 years	15 years	20 years	20 years
Maintenance	4% of TCI	2% of TCI	6% of TCI	7% of TCI
Biomass	70 EUR/t	68 EUR/t	65 EUR/t	60 EUR/t
Electrical energy price	90 EUR/MWh	50 EUR/MWh	150 EUR/MWh	-
Electricity demand	1.7 kW/L	1.3 kW/L	1.2 kW/L	-
Personnel	533	293	232	251
Annual operation time	7008 h	7000 h	7008 h	7008 h

[1]: for local and central plant, respectively.

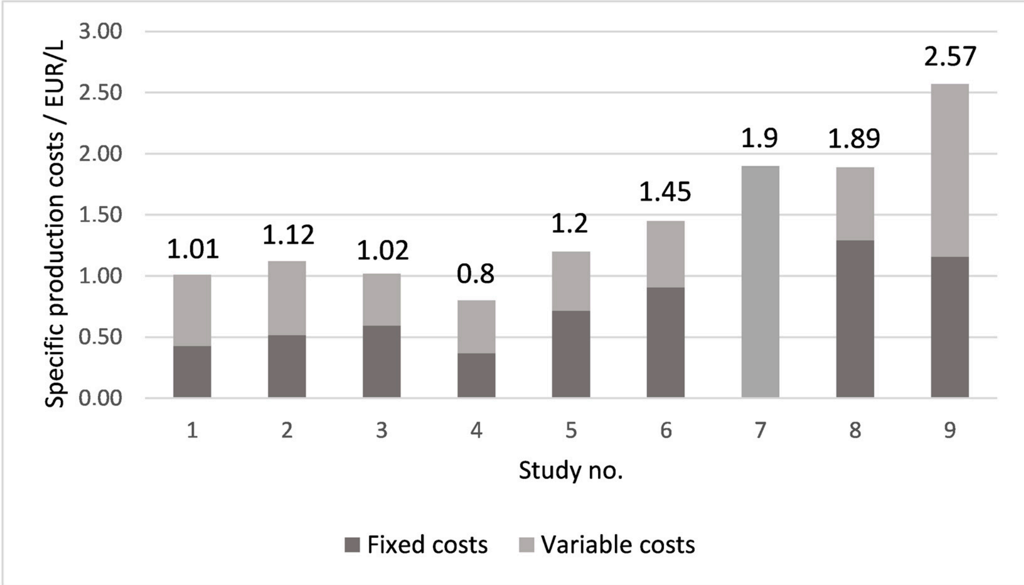


Figure 4. Specific production costs and their composition by fixed and variable costs.

Most of the fixed cost contributions depend on the investment costs and are usually calculated from fixed percentage shares. Therefore, the estimation of the total investment made in the studies earned specific care. To determine the investment in BtL studies, a factor method was most commonly applied. The costs for the main technical components such as apparatus and machines were estimated either on the basis of personal experience, by requesting quotes from companies, or with the help of literature and suitable publications. The adjustment to the required conversion capacity was done by means of degression factors, the values of which were also taken from literature and took into account the different economies of scale for various components. The price was then adjusted to the year in which the plant was built using a price index. This should have compensated for fluctuating raw material costs, especially for steel. After these, and possibly some other adjustments, the so-determined purchase costs were multiplied by factors considering engineering, construction, instrumentation, piping and unforeseen events. The choice and values of these factors was usually individually adapted by the authors. Studies 3, 5, 6, 7 and 8 used this method for the entire processing plant, whereas studies 2 and 4 only used it for the cost estimation of decentralized locations. Study 4 used known costs of a GtL (gas-to-liquid) plant to derive the costs of the central gasification/synthesis plant with appropriate scaling to the desired capacity. Study 2 estimated the costs at 439 million EUR without providing further information.

According to Table 5, large deviations in the determination of the total investment between the studies exist. Studies 2, 5 and 8 calculated almost identical investments with little differences, although they varied greatly in their conversion capacity. The capacity of Study 5 with 1100 MW was almost twice that of Study 8 (600 MW), while the costs of the plants were only 10% more. In contrast, studies 6 and 3 calculated significantly lower total investments at the decentralized location than Study 8 with similar capacities. This pronounced ratio suggests that in addition to economies of scale there were other factors that explained the significant deviations in investments. In two studies, learning led to a reduction in investments: Study 5 included a learning effect in the cost calculation of the decentralized plants, which reduced the costs to an average of 80% of the first one. Study 6 also assumed a cost reduction potential of 15% compared to the first plant.

The level of detail was quite different between the studies. In Study 5, the authors determined costs down to the level of individual technical components, while studies 2, 3, 6 and 8 used a rough approach and summarized the components in less detail or referred to a reference plant. Another difference arose from the type and value of factors applied to the plant purchase costs. Studies 2, 3 and 4 used components supplied as a base value multiplied with sum factors of 3.5, 2, and 5, respectively. Studies 5, 6 and 7 assumes installed components, multiplied by factors of 3.43, 1.65, and 3.18, respectively. Only two of the studies took into account an additional surcharge for working capital, which increased the investment costs by a factor of 1.75 and 1.56, respectively.

In Figure 5, the specific investment costs (SIC) in Euro per kW product are shown for the local and the central conversion plants as well as for the overall investment. The numbers for overall SIC included several local plants, in addition to one central conversion plant, according to the different configurations considered in the studies. The conversion capacities were related to the biomass feedstock for the local plants, to the biosyncrude feed for gasification/synthesis central plants and to the product capacity for the overall process, respectively. In the RENEW EU project SIC values of 1885 EUR/kW were estimated for the bioliq® concept with five pyrolysis plants of 100 MW each and a gasification/synthesis plant of around 400 MW feedstock conversion capacity.

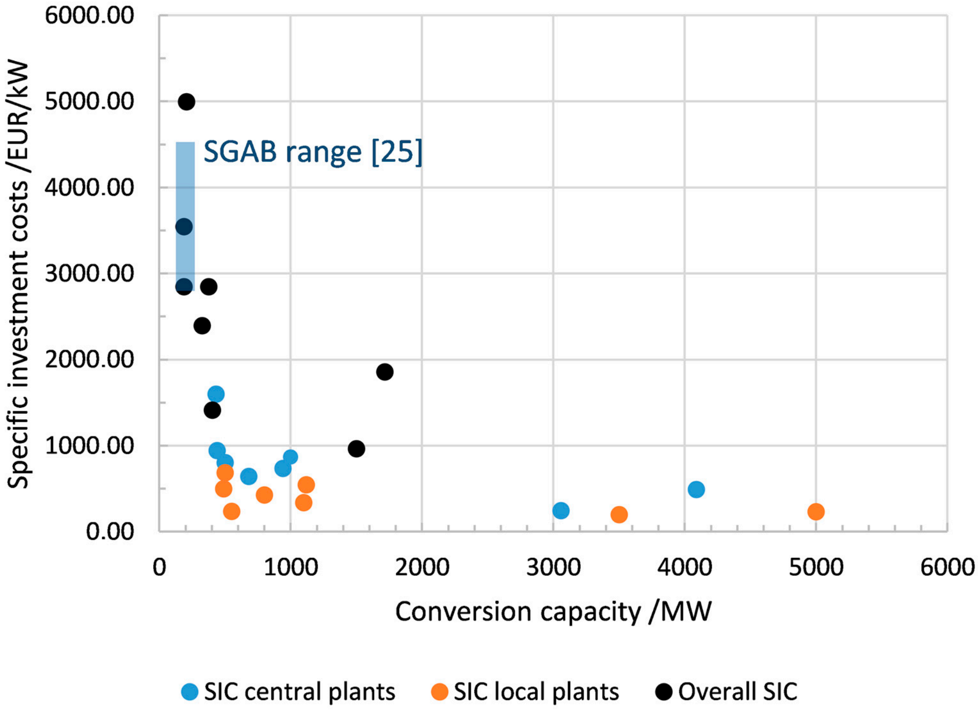


Figure 5. Specific investment costs (SIC) for summarized local and central conversion plants and overall SIC.

Study 8 with 1600 EUR/kW determined about twice the specific investment for the central location compared to studies 3 and 6 with similar conversion capacities. It is very likely that this was due to the significantly larger surcharges that Study 8 added to the equipment purchase costs. With the high level of detail in the cost calculation, Study 5 estimated the costs for a much larger system (941 MW) at comparable costs to studies 2 and 3. Studies 4 and 1, on the other hand, estimated significantly lower specific costs, which seems plausible due to the much higher capacity according to the economy-of-scale effect. Study 4 also presented a special feature in the fact that the central location would be incorporated into an existing refinery complex as a so-called "brown field" facility. The concept, therefore, did not envisage the construction of a new air separation unit, since the required oxygen was bought "over the fence".

Despite the wide spreading of SICs for the bioliq® concepts they were a relatively close match for the range of specific capital costs of 2900–4500 EUR/kW as estimated in a study of IEA Bioenergy Task 41 [21]. This estimation was based on a report on the technology status and reliability of the value chains for advanced biofuels by SGAB [35]. Correspondingly, fuel production costs were calculated to vary between 0.80 and 1.54 EUR/L for gasification-based Fischer-Tropsch fuels with a plant size of 200 MW. Even though the SIC for the capital-intensive construction of the pyrolysis and gasification/synthesis plants appeared to be lower in several studies on the bioliq® process than for other BtL technologies as investigated in the SGAB study, the production costs (see Table 5 and Figure 6) were found to be higher.

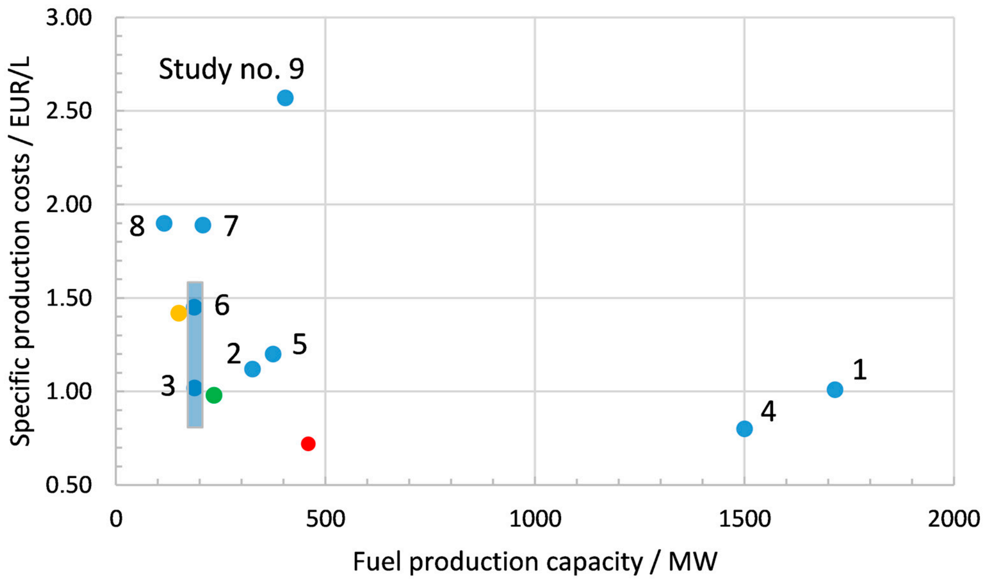


Figure 6. Specific fuel production costs in EUR/L for the different studies investigated (blue points), and costs from other studies blue bar [25], red point [7], green point [36] and yellow point [37].

3.2.2. BtL Production Cost Distribution

The percentage contribution of the individual cost items to the specific production costs is shown in Table 5 for all studies except no. 7, in which this information was not provided. The total investment costs for both the local as well as for the central plants are given. Since not clearly stated in all studies, it is assumed here that green field plants were constructed. In all studies, cost factors like maintenance and tax & insurance were related to the investment costs. In some studies, personnel costs and overhead were also related also to the total costs, while in other studies detailed calculations were carried out to determine the staff requirements for plant operation and the overhead composition, including administration, marketing, medical and safety services, licenses and patents, as well as research.

In the following sections the effect of the most relevant economic parameters presented in Table 5 together with the relative share of cost contributions to the production costs, are discussed. It becomes obvious that the costs for biomass and the cost of capital made up the largest share. In Study 1, the percentage of these two items was around 85%, but they had the smallest proportion in Study 8 with approx. 53%.

The annual capital costs were directly dependent on the investment costs, the depreciation period and the imputed interest rate. Furthermore, the construction time of the plant also influenced the cost of capital due to the time lag before turnover was generated. However, the latter was only taken into account in studies no. 1 and 6. In all studies, except no. 6, the capital costs ranged between 20% and slightly above 30%. Related to the investments, Study 4 showed the highest percentage of capital costs with nearly 15%. This was due to the significantly shorter depreciation period of 10 years. The annual cost of capital in Study 5 was approximately 8% and had the lowest value compared to the other studies. This can be traced back to the much lower imputed interest rate, which was 5% and thus below the average interest rate of 7% in the other studies.

The costs for maintenance and servicing were also directly dependent on the total investment. The average values used in each study are also given in Table 5 and range between approx. 2% and 6% of the capital expenditures. This resulted in a cost contribution between 6 and 18% of the specific production costs.

Studies 1 and 6 also included the construction time of the plant into their estimates. The costs incurred due to a lack of income during this period and could be determined from the annual cost of capital using the data provided for the depreciation period and the interest rate. They resulted from the difference between the cost of capital and the annuity. For Study 1, the annual capital costs increased by around 14% by taking into account the construction time, and for Study 6 by as much as 17%. This is an increase of 3% and 6%, respectively, in the total annual costs.

The cost of the biomass and the biosyncrude transport costs made a substantial contribution to the production costs of the FT fuel. The share of biomass costs fitted well into other studies revealing 40–60% of biomass costs for production of Fischer-Tropsch hydrocarbons via biomass gasification [8] except for studies 7 and 9 with lower shares due to larger annuities. The costs of the biomass supplied to the plant gate varied between 63 and 72 EUR/t. However, market effects e.g., due to the increased demand of raw material were not taken into account, but could be expected, given the enormous plant capacities of up to 9 Mt in Study 1. Increasing feedstock costs in a sourcing area would lead to the acquisition of new areas with a greater distance, thus increasing feedstock supply costs with regard to limited availability, which, for crop residues in Europe, is estimated to be around 212 Mt/a [38]. For the transport of biosyncrude from the local to the central plants, no explicit information could be found in studies 6 and 7; they are thus included in the costs for the biomass feedstock. However, despite a surcharge for transport, these values were similar to the costs of biomass free plant in the other studies. For the latter, the surcharge for transportation varied between € 7 and € 19 per ton of slurry. This cost contribution also became significant for large scale plant constellations with biosyncrude quantities of up to 6 Mt/a. The differences in the costs for biomass free plant and the biosyncrude transport arose from different assumptions for raw material costs, the sourcing radius of the biomass and its transport costs, the distance of the decentralized locations to the central location and the means of transport used. In contrast to fossil fuels, this kind of considerations will be of decisive importance for scaling biomass-based conversion plants. However, on the basis of the studies investigated here, no detailed comparison can be concluded.

The costs for energy were mainly dependent on the plant concept and the corresponding energy flows. Furthermore, there was a dependency on the specified specific energy prices, which, in turn, differed drastically for each study. This influence can be discussed disregarding the studies no. 1, 4 and 7. Due to the self-sufficient concept, energy prices were not relevant for Study 1. For studies 4 and 7, the corresponding data were not provided. It should be noted that the studies mostly offset the excess electricity produced at the central location with the electricity required at the decentralized locations. Since this disregarded any usage fees for the electricity grids, the electricity required, unless otherwise stated, was purchased at the decentralized location and the excess electricity sold at the central location at the same price. This did not affect the calculated costs, but a comparison of the energy costs could be performed. Only Study 3 took a cost difference between feed-in tariffs and electricity consumption into account. A comparison of energy price and demand, as well as the share of electricity cost as given in Table 5, shows that the fixed electricity price had an influence on the cost contribution of electrical energy to the production costs, which should not be underestimated. While the specific electricity demand for Study 2 was more than twice that of Study 8, the cost share per liter of FT fuel differed only slightly due to the significantly higher electricity price in Study 8.

Table 5 also provides information on personnel costs. Studies 3 and 8 stated the annual personnel costs without specific employee wages and number of employees. An average wage of € 60,000 was assumed for these studies, and the resulting number of employees was calculated based on that. A comparison of the personnel requirements was possible by calculating a specific employee requirement per production site. For Study 3, a staffing requirement of around 50 employees was calculated with an average salary of 60,000 EUR/a. Due to the number of ten decentralized and one central location, a personnel requirement of approx. five employees per location was calculated. Compared to the other studies, this is an exceptionally low value. For the other studies, a trend of decreasing personnel requirements with increasing plant size can be seen, which is plausible with regard to economies of scale. Study 2 was another exception; here, the personnel requirements appeared to be very high compared to the size of the plant and the other studies.

In Figure 6, the specific production costs found in the investigated studies are compared to other data for gasification based hydrocarbon fuels compiled within a study of IEA Bioenergy [21], which are covered by the blue bar. Calculated for a plant size of 200 MW, different technical developments including the bioliq® process were considered in that study. By optimization, an additional cost reduction potential of up to 15% was estimated by that group for hydrocarbon fuels. The data point taken from Dimitriou et al. [7] was generically calculated for FT fuel produced via entrained flow gasification of woody biomass, marking the lower end of cost estimates performed on BtL fuels. For corn stover, Wang et al. [36] estimated around 1 EUR/L of FT fuel at a production capacity around 240 MW. Finally, a TEA study including the bioliq® process within the RENEW project resulted in 1.42 EUR/L of fuel [37].

In general, there was a clear trend according to the economy of scale. However, for the decentralized/central bioliq® process requiring several plants at different locations, this benefit became apparent only when large conversion capacities were achieved [18,23,37]. It is only then that the decentralized pretreatment for energy densification overcompensated the increasing transportation costs for the direct supply of a large scale synfuel production plant. On the other hand, these considerations were conducted without the important relation to biomass availability and supply as discussed in the introduction. Among the studies examined here, only in the BioBoost study [33] a logistic model was taken into account within a simulation, identifying areas for biomass supply in central Europe and creating a scenario of conversion sites and capacity for pyrolysis and gasification/synthesis plant with minimum costs. A similar study was conducted by Li and Hu [39] based on a supply chain design relevant for the collection of crop residues in Iowa, USA. For conversion, central processing by pyrolysis and gasification, as well as central gasification with decentralized pyrolysis plants, were compared to direct central, as well as decentralized gasification of the biomass. The decentralized plants varied from 2000 t/d to 6000 t/d of feedstock conversion capacity, while the central units were fixed to produce around 1.5 Mt of diesel fuel equivalent. It turned out that the concept with decentralized pyrolysis was better than the centralized one (0.82 vs. 0.84 EUR/L). This way, the decentralized concept could outperform the single site process concept, but not the concept with direct gasification at 0.75 EUR/L, which won the trade-off between biomass supply and operational and capital costs of the processing plants. One reason may be that the sourcing radius considered here did not exceed 200 miles, so that the hybrid concept could not invert that trade-off.

Regarding the plant configurations used in the different studies investigated, some conclusions may be drawn. Studies 1 and 4 were based on not too realistic scenarios within central Europe because the overall feedstock capacity appears too large (demanding for nearly up to one third and one twentieth of the agricultural residue potential in Germany and Europe, respectively [38,40]). Scenario 9 considered straw supply chains, but did not allow for multiple feedstock which would reduce costs The overall conversion capacity in study 7 appeared as too small to benefit from the bioliq® concept, resulting in relatively high, but not unreasonable, production costs. According to the state of the art in fast pyrolysis technology today, a feedstock conversion capacity of 50–100 MW can be assumed as realistic for future plants. That way, studies 3, 5, 6, and 8 would be realistic scenarios also in terms of the assumed gasification capacities from 500 to beyond 1000 MW in modular reactors. In study 3, investment cost were unreasonably below the range given by the

IEA study [21] resulting in too low production costs. In study 8, no electricity was by-produced to generate additional revenues. Thus, studies 5, 6, and 8 proviedreasonable cost estimates from a useful combination of useful plant configuration, estimated investment and operational costs and economic parameters, resulting in a production cost range of around (1.5 ± 0.3) EUR/L.

3.3. Model Variations

This chapter examines the effects of variations in some of the economic key parameters discussed above. First, the time dependency of the investment estimate is checked using a time dependent plant cost index. Also, the direct effect of learning effects on the production costs is examined. Then, the sensitivity towards the cost items "Investments" and "Biomass and Transport" is investigated. Finally, the cost models are harmonized; the annual capital costs and costs for maintenance and servicing are adjusted to the percentage of the investments for all studies. The operation time is also fixed to one value. The variations are intended to yield a worst case scenario for which the value of the study with the highest percentage is adopted, and a best case scenario in which the lowest value is assumed.

The estimation of investments in chemical industrial plants depended on the year in which the plants are planned to be built. This is due to numerous factors, which in turn depended on global economic developments, such as the price of steel. Such chemical plant cost indices are, for example, the Chemical Engineering Plant Cost Index (CEPCI) and the PCD index for chemical plants in Germany (https://www.chemietechnik.de/anlagenbau/pcd-preisindex-fuer-chemieanlagen-4.html, accessed on 12 April 2021), published by the Chemie Technik journal on a quarterly basis. During the time in which the studies were conducted, significant fluctuation of the average cost indices took place. Therefore, a clear development of investment costs cannot be concluded. From the cost curve fluctuations, deviations of ±5% can be assumed between 2008 and 2015.

The plant configuration in Study 5 made use of eleven pyrolysis plants with a thermal fuel capacity of 100 MW each. For the first plant, investments of approx. 42.6 million EUR were estimated. For the following plants, savings due to the construction of additional plants of the same type were assumed using a progress factor, resulting in the 11th plant costing 79% of the first plant. Study 2 deliberately did not take into account the effect of technological learning because the construction of the plants should have occurred, more or less, in parallel. The investments for a pyrolysis plant for wood and straw biomass with an input power of 200 MW amounts to approx. 85.4 million EUR. Study 8, on the other hand, anticipated investments into six pyrolysis plants with 100 MW each to the amount of 57.2 million EUR. By adapting to the model used in Study 5, a progress factor was also applied to the cost estimates of studies 2 and 8, which led to lower investments for the 4th and the 6th plants of 89 and 85%, respectively, as compared to the original cost estimates for the local plants. The fuel production cost would be reduced by about 2% in both cases. On the other hand, without learning effects, the production costs in Study 5 would increase by 4% due to the large number of plants, which significantly benefited from the learning effect.

The investment, and the biomass and transportation costs, significantly contributed to the production costs. Therefore, their effect was studied by increasing their values by 10 and 30%, without changing any other study-specific economical parameter. In the first case, as depicted in Figure 7, the fuel production costs rose by 4–7% and 2–7%, respectively, when the associated investment and feedstock supply costs rose. When the costs were increased by 30%, the production costs were found to rise accordingly by 11–17% and 7–17%, respectively. Thus, the changes in investment and feedstock supply cost had a similar influence on the fuel production cost, even though the cost share of biomass costs was larger than that of the investment costs (see Table 5), which were only part of the capital costs. The smallest effect of biomass and transportation costs, which were not separated because of a lack of information in the studies, was found in studies 6 and 8, where the share of feedstock supply in the production costs had the lowest values.

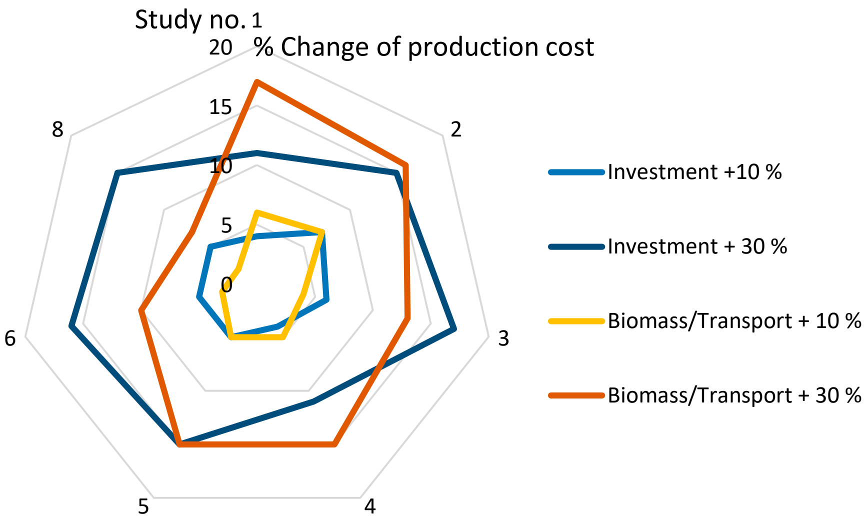


Figure 7. Change of production cost by increasing the investment and biomass/transportation costs by 10 and 30%.

In the following, the effects of adjusting some economic key parameters on the calculated production costs are examined. Namely, the percentages of the investment costs to calculate the capital costs and the costs for maintenance and repair, as well as the operation time are fixed. Worst case and best case data were determined using the highest and the lowest value of these parameters from the studies to calculate the production costs. The resulting deviations are compiled in Figure 8. By aligning these factors of the cost model, quantitative differences can be shown that arise solely from the choice of the cost model, since the balance of the material and energy flows, the determined investments and the specific costs of the operating resources maintain the study-specific values.

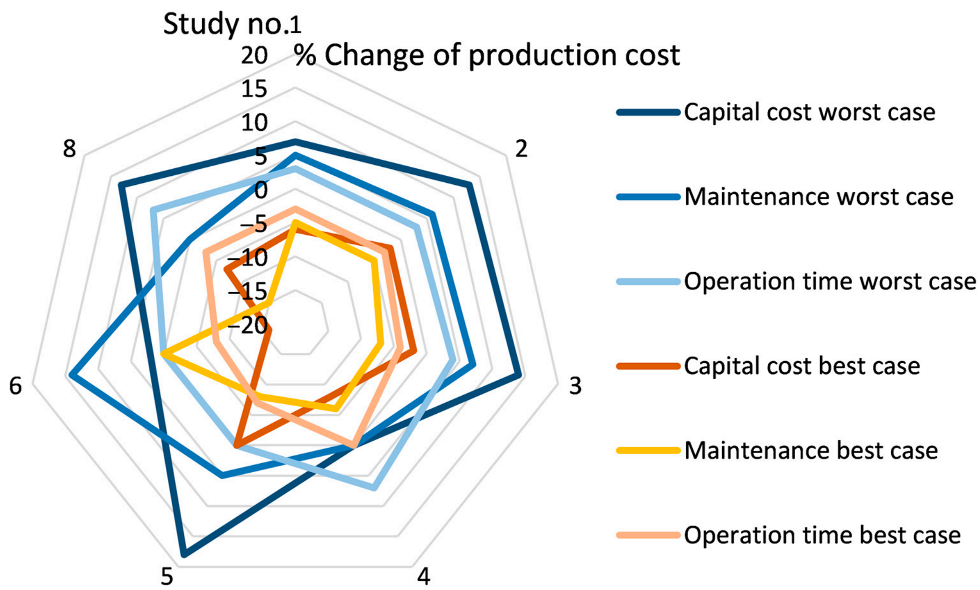


Figure 8. Changes of production cost in percentages by worst- and best-case adjustments of shares for capital cost and maintenance and of operation time.

In the worst-case scenario for the capital costs of 14.3% (see Table 5), the production costs for five of the six studies increased significantly by 7% for Study 1 to 18% for Study 5. The effect on production costs for Study 6, with 2%, was much lower. In contrast to this, the best-case scenario (8.8% of investment costs) for Study 6 showed a production cost reduction by 16%, while it was around −2% to −7% in all other studies. These differences can be explained by the different dependency of the manufacturing costs on the capital costs.

In the same way as the cost of capital, the effects of variations in the costs of maintenance and servicing on the manufacturing costs were examined and are displayed in Figure 8. In the cost models of the studies, the highest value occurred in Study 4, and the lowest value occurred in Study 6. The worst-case scenario, with a cost share of 6% of the investments for maintenance and repairs, led to an increase of production costs by more than 5% in all studies, and up to 14% in Study 6, where originally a percentage of 2% was used for maintenance. Since the cost model of Study 8 also made use of a cost share of close to 6%, the effect of 0.1% was very low. In the best-case scenario, the share of maintenance and servicing was only 2% of the investments. This adjustment reduced the production costs of the studies by between 5% and 12%.

The operation time for the production plants was assumed to be between 7000 and 8000 h/a, which had a direct effect on the variable costs and the amount of fuel produced. This resulted in an increase in production costs of up to 7% in studies 4 and 8. In the best-case scenario, with 8000 h of operation per annum, the production costs in studies 5 and 6 reduced by 7% and 8%, respectively.

So far, the economic parameters have been altered without changing the other parameters used in the different studies. Therefore, the effect of accumulated worst-case and best-case values on the change of production costs have also been estimated. For the worst case, capital costs were calculated at 14.3% and costs for maintenance and repairs at 6% of the investments for 7000 h of operation time. Figure 9 shows that in this scenario the study-specific production costs increased by 7% to 27%. In the best-case scenario, with an operation time of 8000 h/a, the capital costs were 8.8% and the costs for maintenance and repairs were 1.9% of the investments. In the best case, fuel production costs may be reduced by 22%.The results of these scenario variations showed large differences in the effects on manufacturing costs between the studies. This is a consequence of the differently weighed proportions of the investment-dependent costs in the production cost calculation of each study and the difference in the values between standard and variation scenarios. The pronounced cost differences, while maintaining the study-specific material and energy flows and specific variable costs, underline the strong dependency of the calculated production costs on the cost model used.

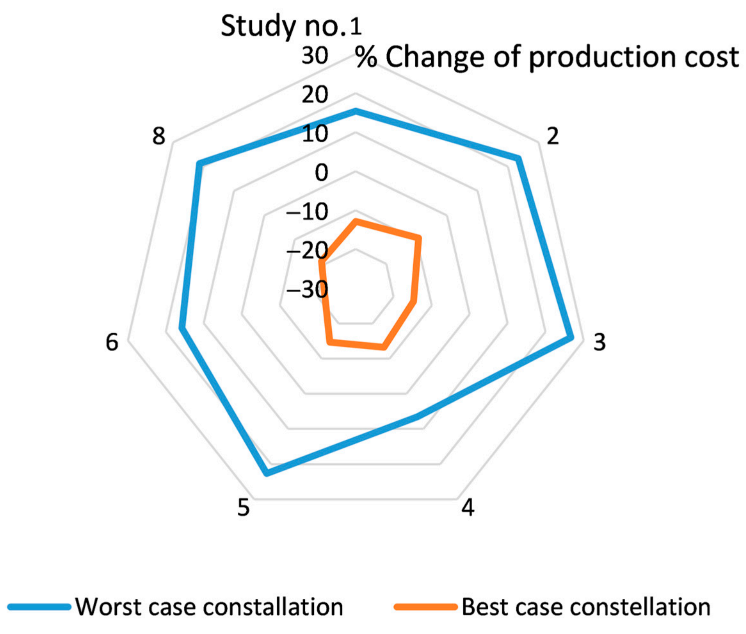


Figure 9. Change of production cost by using accumulated best- and worst-case economic parameters.

4. Conclusions

In this study, investigations by various research institutions on the costs for the production of BtL fuels using the bioliq® process were analyzed and evaluated. Both their specific approach with regard to the material and energy flows and the cost model used to calculate the specific fuel production costs were taken into account. Differences in conversion efficiency were large in those cases when assumptions for electricity generation at the central location were taken into account. However, since all studies were based on published data of the bioliq® process, the fair agreement in the calculated efficiencies was not surprising. In relation to the energy content of the fuel produced, the estimated conversion efficiency of all studies showed values around (36 $\pm$ 3)%. This is below the data provided by the survey on advanced fuels of IEA Bioenergy [21] but can be explained by the additional efforts of pretreatment by pyrolysis. In agreement with other studies on BtL and advanced fuels it was found that the largest cost items were attributable to biomass (including transport of the biosyncrude) and the capital costs. Comparison of the specific investments per installed megawatt of the plants showed that, in addition to economies of scale, particularly the origin of the equipment purchase costs and the cost factors applied to them, induced significant variations. Major differences between the studies also occurred in the cost of capital calculation. Significant deviations were already found in the depreciation period and the amount of the assumed interest rate. The effect of the dates of origin of the studies could not be clearly determined because of the intense fluctuations of chemical plant costs in the investigated period of time but could be assumed to contribute $\pm$5% of the production costs. Two studies took a construction period that accounted for a proportion of the fuel production costs into account, which should not be underestimated. Even though staff costs were below 10% in all cases, differences by a factor of four could be found due to the strength of the required workforce, assuming that all plants were planned for being constructed and operated in Germany. Additional cost variations may occur due to different staff costs and other issues related to cross-border activities in addition to equipment purchase. The use of learning potentials for the several local plants led, in one case investigated, to cost savings of around 20% when more than 10 plants are constructed. The effect on the fuel production costs was around 3% in this case. Finally, adjustments to the cost model of the studies showed the importance of the leverage of financing. By harmonizing the depreciation period and the assumed interest rate, the production costs changed from $-$16% to +17%. Similar effects were achieved by adjusting the costs for maintenance, servicing and the plant operation time. In the best-case scenario, which adopted the most beneficial combination of economic parameters used in the studies, the fuel production costs could be reduced by up to 21%. The most expensive variant in the opposing worst-case scenario, on the other hand, raised costs by up to 27%. That way, the harmonization of economic parameters generated an uncertainty that contributed, by more than half to the cost accuracy level class 4 of the AACE classification [41], of a 15–30% lower and a 20–50% higher limit relevant to a preliminary estimate based on a conceptual design be available at TRL6.

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