

Cost estimate for biosynfuel production via biosyncrude gasification

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Abstract: Production of synthetic fuels from lignocellulose like wood or straw involves complex technology. Therefore, a large BTL (biomass to liquid) plant for biosynfuel production is more economic than many small facilities. A reasonable BTL-plant capacity is ≥ 1 Mt/a biosynfuel similar to the already existing commercial CTL and GTL (coal to liquid, gas to liquid) plants of SASOL and SHELL, corresponding to at least 10% of the capacity of a modern oil refinery. BTL-plant cost estimates are therefore based on reported experience with CTL and GTL plants. Direct supply of large BTL plants with low bulk density biomass by trucks is limited by high transport costs and intolerable local traffic density. Biomass densification by liquefaction in a fast pyrolysis process generates a compact bioslurry or biopaste, also denoted as biosyncrude as produced by the bioliq[®] process. The densified biosyncrude intermediate can now be cheaply transported from many local facilities in silo wagons by electric rail over long distances to a large and more economic central biosynfuel plant. In addition to the capital expenditure (capex) for the large and complex central biosynfuel plant, a comparable investment effort is required for the construction of several dozen regional pyrolysis plants with simpler technology. Investment costs estimated for fast pyrolysis plants reported in the literature have been complemented by own studies for plants with ca. 100 MW_{th} biomass input. The breakdown of BTL synfuel manufacturing costs of ca. 1 €/kg in central EU shows that about half of the costs are caused by the biofeedstock, including transport. This helps to generate new income for farmers. The other half is caused by technical costs, which are about proportional to the total capital investment (TCI) for the pyrolysis and biosynfuel production plants. Labor is a minor contribution in the relatively large facilities. © 2009 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: biosyncrude; synthetic biofuel; fast pyrolysis; gasification; syngas; production cost

Background

After exhaustion of the proven and economically recoverable fossil oil, gas and coal reserves,¹ biomass remains the only renewable carbon resource for

organic chemicals and fuels. Thermochemical, biochemical and physiochemical biomass conversion processes leading to a variety of carbon-containing products will be combined in extended, complex biorefineries. These represent the organic chemical industry of the future.

At present, road, air and ship transport and about 80% of raw materials for organic chemistry rely almost exclusively on crude oil. A shortage of oil and high fuel prices would cause serious trouble in the world economy. Substitution of the dwindling oil resources is an urgent and unavoidable global challenge in view of the raising oil prices.

Coal and natural gas can be converted into liquid synthetic fuels with a much higher quality than conventional oil-derived fuels. These synfuels are sulfur-free and can be tailored for a new generation of more efficient combustion engines. Thermochemical CTL (coal to liquid) technologies have been applied in Germany during World War Two for motor fuel production up to 0.6 Mt/a in 1944. At present, the largest CTL plants with 6 Mt/a transportation fuel production capacity, are operated by SASOL in Secunda, South Africa. Also large commercial GTL (gas to liquid) plants have been operated by SASOL and SHELL since 1993 and even larger GTL plants with capacities of several Mt/a based on cheap natural gas are being planned in Qatar and Nigeria.

CTL and GTL synfuel technology is based on synthesis gas – a mixture of CO and H₂ – as a versatile intermediate, but is more complex and expensive than an oil refinery. It will become competitive if the raw materials coal and gas are considerably cheaper than oil. In July 2008, at a crude oil price above slightly US\$140 /bbl, competitiveness has been attained, that is, if the coal-, gas- and biomass-to-oil price ratio does not significantly rise in the future. But the future price levels are not reliably predicible.

Many different organic products can be manufactured by selective syngas conversion reactions with different catalysts at certain temperatures and higher pressure. Examples are methanol, dimethylether (DME), olefins, methane (SNG), hydrogen, FT-diesel and other products. There are also pathways to transportation fuels via methanol by an MtG (methanol to gasoline) or MtS-process (methanol to synfuel) as developed by LURGI.²

Methane in the form of natural gas – and also SNG – is already used as motor fuel; in the future, hydrogen may also be used in fuel cell vehicles. Neat DME is well suited as an environmentally friendly diesel fuel, particularly in low-temperature climates.³

BTL (biomass to liquid) plants apply the known technology of the CTL and GTL plants with minor modifications. The

tail-end steps after generation of a clean syngas with the desired H₂/CO-ratio are identical for all XTL-processes, since it does not make a difference if the syngas has been produced from coal, natural gas or biomass. Tail-end steps are considered as state-of-the art. The front-end steps for lignocellulosic biomass – which can contain much ash – have more in common with the gasification technologies suited for ash-containing coals. Front-end steps for efficient biomass gasification still require further development work.

The early conceptional stages of a biosynfuel production process must be accompanied by preliminary order-of-magnitude cost estimates and serve as a selection guide to the most economical route. Published information from commercial CTL and GTL projects can help in evaluating the economy of various BTL technology variants. But sensitive economic information is usually kept secret and not available in the public literature. The purpose of this paper is a crude ca. ± 30% biosynfuel manufacturing cost estimate for the Karlsruhe biosyncrude gasification process, bioliq[®]. The methodology is explained in sufficient detail and allows quick cost adjustments for different basic input data and is applicable also to other BTL techniques. Economic evaluation and comparison of various BTL technologies with this method is expected to result in much better relative accuracies than 30%. This task remains to be done.

The biosyncrude gasification process bioliq[®]

The Karlsruhe BTL process, bioliq[®], is outlined as a block diagram in Fig. 1.^{4,5,6} Key technology is an oxygen-blown, slagging-entrained flow gasifier operating at high pressure above the downstream synthesis pressure to avoid expensive intermediate syngas compression. The reaction chamber in the selected GSP gasifier is enclosed by a membrane wall, cooled with pressurized water and can accommodate feed with much ash. At the high gasification temperature above ca. 1200°C, a slag layer about 1 cm thick with a honey-like viscosity drains down at the inner surface of the gasification chamber and protects the wall against corrosion and erosion. A cooled membrane wall has a low heat capacity and thus permits fast start-up and sudden shut-down procedures. Because of the high gasification temperature, the raw syngas is practically tar-free and has a low CH₄ content; thus simplifying downstream syngas cleaning.

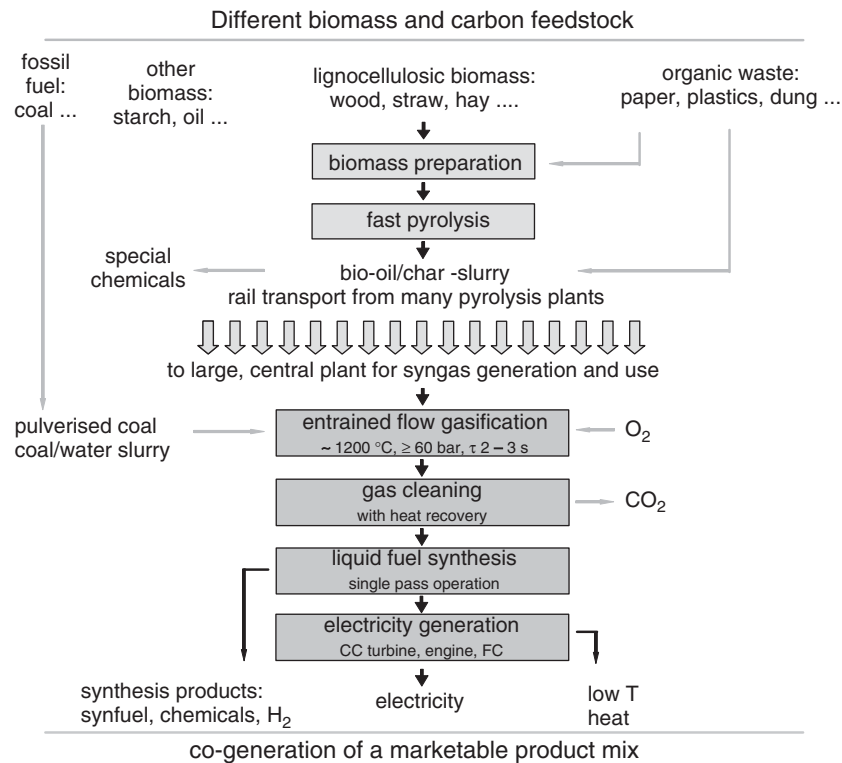


Figure 1. Simplified flow sheet of the biosyncrude gasification process.

The gasifier characteristics mentioned above favor a downstream synthesis but are obtained at the expense of somewhat higher oxygen consumption and some more effort for the preparation of a pumpable gasifier feed. Principally, any pumpable fluid feed, which can be pneumatically atomized with oxygen and has a heating value above 10 MJ/kg is suited as the entrained flow gasifier feed. A pre-conversion of biomass to such a pumpable feed form increases the feedstock flexibility considerably.

For the abundant lignocellulosic biomass like wood or straw, fast pyrolysis (FP) has been selected as the most economic and convenient pre-treatment method for liquefaction. Fast thermal decomposition of dry lignocellulose at about 500°C in the absence of oxygen generates a high yield of pyrolysis liquid and low yields of pyrolysis char and gas. The small amount of pulverized pyrolysis char can be completely suspended in about twice as much pyrolysis liquids to form a stable bioslurry or biosyncrude. This suspension is warmed up for viscosity reduction and transferred with a screw or plunger pump into the highly

pressurized gasifier chamber for pneumatic atomization with pressurized oxygen.

Free-flowing slurries are a most useful feed form for the pressurized entrained flow gasifier. The biosyncrude is well suited for energy-dense storage and transport, resulting in lower transportation costs and large biomass delivery areas. In Fig. 2, the relative volume of biomass at the example of wood and straw, that of the separate pyrolysis products, and that of the final mixture are shown. The volume reduction and thus energy densification is considerably higher for straw than for wood. It is expected that for this kind of process, low-grade biomass of low volumetric energy density is much more similar to straw than to wood. Biosyncrudes produced in many regional FP plants with ca. 0.1 GW_{th} biomass input (ca. 200 t/a air-dry lignocellulose) can then be transported economically and in an environmentally friendly fashion in silo wagons on electrified rail over very long distances to a large, central biosynfuel and chemicals production complex (biorefinery) with an input capacity of several GW_t.

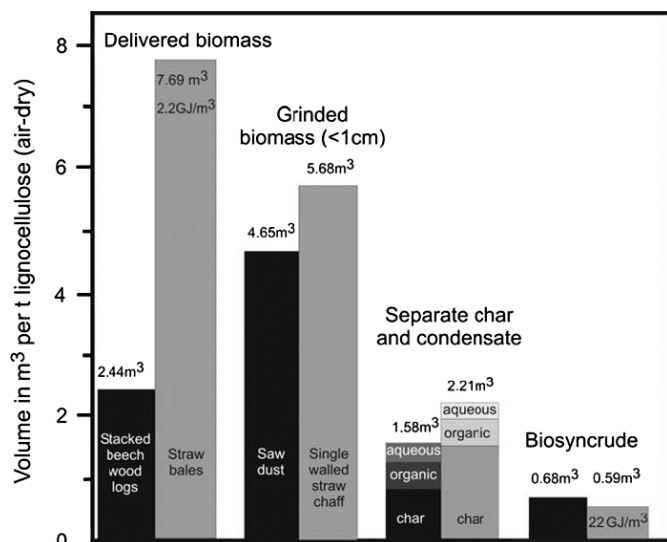


Figure 2. Relative volumes of biomass, biosyncrude and intermediate products.

General economy aspects

Some general plant characteristics can lead to substantial cost reductions, independent from the selected technology.

Large plant size

A simplified estimate of the contribution of the technical part to the biosynfuel manufacturing costs is proportional to the total plant capital investment costs (TCI), which play a dominant role in the economy. There are no BTL facilities in operation today; therefore reliable TCI estimates are difficult to perform and are expected to show an uncertainty in the order of $\pm 30\%$. This is almost a factor of two between the minimum and maximum value. The capital and related costs per year – beside raw materials, utilities and labor – are assumed to be in a 20–28% range of the TCI for this type of chemical facilities.⁷ For this paper we use a 25% share for a depreciation period of 10 years. For single-train plants, investment costs do not increase linearly with scale, but the cost ratio is approximated by a power relationship of the capacity ratio (Eqn 1).

$$\frac{\text{cost}(\text{new})}{\text{cost}(\text{reference})} = \left[\frac{\text{capacity}(\text{new})}{\text{capacity}(\text{reference})} \right]^{0.7}$$

With this cost degression equation, the cost of a new plant can be estimated from the known cost and capacity of a

reference plant for a scale change of an order of magnitude without technology change. A degression exponent of 0.7 means, that a capacity increase by a factor of 10 can be obtained with an investment cost increase of only factor 5. This is equivalent to a substantial reduction in the specific investment costs to about half. All plants should therefore be as large as reasonably possible. A reasonable maximum size for the FP plants is given by the feedstock delivery distance (ca. 100 MW_{th}). For a biosynfuel production plant an output capacity one order of magnitude smaller than that of a conventional mineral oil refinery can be assumed, say around 1 G t/a.

Brown field plant site

The selection of a plant site within an already-existing industrial complex ‘brown field’ site like an oil refinery or a chemical complex enables considerable cost savings. Rail access is considered as particularly important, since this allows the use of the efficient, cheap and clean electrified rail for transport. In a ‘green field’ site, a number of additional auxiliary facilities must be erected in addition, thus increasing the capital expenditure (capex).

Cost reduction by learning

If the same type of facility is designed, built and operated several times in succession, investment as well as operating costs can be reduced to a certain extent by learning from accumulated experience. The investment and operating costs in the sequence of stepwise improved plant versions are assumed to decrease exponentially with the number of plants built. It is reasonable to set a lower TCI limit, e.g., at about two-thirds of the expenditures for the first plant.

In the Karlsruhe bioliq[®] concept, the large central BTL biosynfuel complex is supplied with biosyncrude from many FP plants. The large number of pyrolysis plants supplying a single biosynfuel plant includes already considerable cost reduction by learning. In addition, this is amplified by the simultaneous order of equipment for several plants, erected in convoy mode. Replication saves costs for engineering and repeated equipment production. For the following, a capital investment cost estimate for pyrolysis facilities near the lower limit has been assumed.

Biomass Transport Costs

Biomass transport costs have a constant contribution for loading and unloading and increase linearly with the transport distance proportional to the square root of the supply area or (capacity)^{0.5}. But this is overcompensated by a plant TCI decrease proportional to the (capacity)^{0.7}. The Karlsruhe bioliq[®] concept eases the operation of large BTL plants with production capacities of > 1 Mt/a, which becomes possible by rail transport of the energy-dense biosyncrudes; this is far more economic than the operation of many small BTL plants.

Transport costs for biomass and biosyncrude are reported in Leible *et al.*⁸ and shown in Fig. 3 per t of produced biosynfuel. For simplicity reasons the transport costs in Fig. 3 have been linearized: zero distance contributions are mainly for loading and unloading. In case of rail transport, this is given for straw with 30 km truck pre-transport to the next rail station. Long-distance biosyncrude transport by rail is favored due to the low cost increase with distance. In Table 1, transport costs have been calculated for 1 t of biosynfuel, based on the following mass yields: 7 t airdry straw → 6 t dry straw → 4.7 t biosyncrude → 1 t biosynfuel (diesel plus naphtha).

In first approximation, a biomass collection radius of x km corresponds also to about x km average road transport distance. A 30 km collection radius (area ca. 3000 km²) by tractor in central EU results in an FP plant input capacity for surplus cereal straw (ca. 45% of the total straw harvest) plus stem wood harvest residues of ca. 0.2 Mt/a airdry biomass (LHV 4 kWh/kg). This corresponds to 100 MW thermal input at 8000 h/a operation. About 40 of such FP plants are needed to feed a central biosynfuel plant with biosyncrude for about 1 Mt/a motor fuel production (Fig. 4).

At a delivery distance above about 65 km (point of intersection in Fig. 3), direct transport of airdry straw by trucks becomes more expensive than the local supply of many regional FP plants by tractor followed by rail transport of biosyncrude in silo wagons to a central synfuel plant. A supply radius of only 65 km in the central EU for an integrated BTL plant with an FP plant and biosynfuel production at one central site with residual straw and forest residues as main feedstock results in 0.2 Mt/a of biosynfuel production. This corresponds to only 2% of the capacity

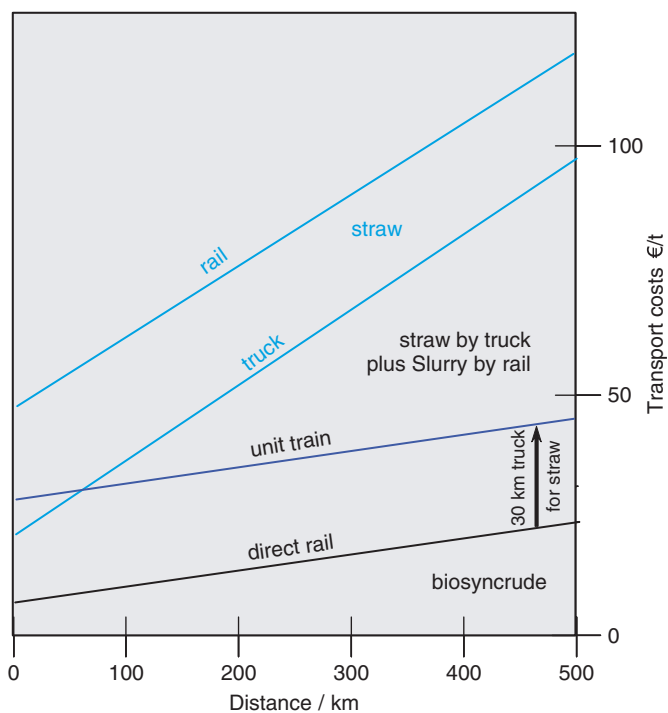


Figure 3. Straw and biosyncrude transport costs by rail or truck, (empty back) for 1 tonne of biosynfuel.

legend:	– x = km distance,	y = €/t dry biomass
straw:	– dry straw by truck:	y = 19 + 0.15 x
	– dry straw by rail, plus 30 km truck transfer to station:	y = 46 + 0.14 x
biosyncrude:	– biosyncrude by truck:	y = 6 + 0.133 x
	– biosyncrude transport by rail:	y = 6.5 + 0.033 x
	– rail plus 30 km truck biosyncrude transfer to station:	y = 13 + 0.033 x

Unit train: 30 km truck transport of wood or straw to FP plant plus biosyncrude transport by rail to synfuel plant with a complete 24-wagon train

of a modern ca. 10 Mt/a oil refinery and seems to be too small from an economic point of view. On the other hand, rail transport of biosyncrudes does not depend much on transport distance. Even huge and more economic biosynfuel plants can be supplied reliably with compact pyrolysis products by electrified rail. Huge biorefinery plants for

Table 1. Comparison of long-distance and total transport costs per tonne of biosynfuel.

Distance	Rail transport			Truck transport		
	100	250	500	100	250	500 km
Transported material:						
7 t airdry straw ≈ 6 t dry straw,	360	486	969	204	339	500 €
4.7 t biosyncrude transport	46	69	108	91	184	341 €
plus €126 for 30 km transport of 7 t airdry straw per tractor to pyrolysis plant results in total costs of	172	195	234 €			

Legend: total transport costs in bold

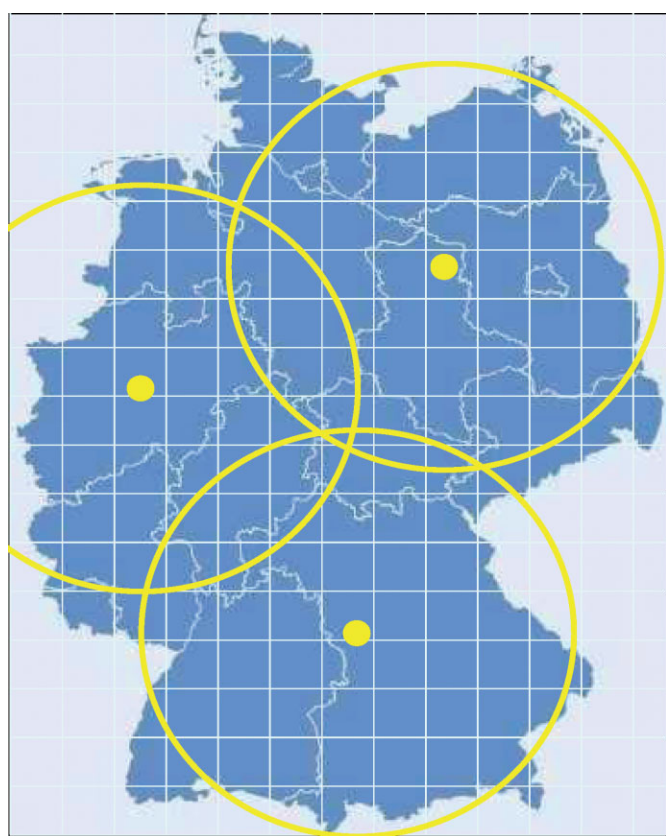


Figure 4. Schematic supply areas for fast pyrolysis and biosynfuel plants in Germany.

Legend: squares: 0.1 GW fast pyrolysis plants
 0.2 Mt/a airdry straw, delivery radius 30 km
 circles: 3.5 GW biosynfuel plants
 4.7 Mt/a biosyncrude, 1 Mt/a biosynfuel

synfuels and organic chemicals will probably emerge gradually with the exhaustion of cheap oil and gas. During an intermediate start period, they are not only fed with

biomass but also with the more abundant and still available coal as a secure co-feed.⁹ This will be helpful for market introduction.

Local traffic density

A small integrated 0.5 GW BTL plant with only 65 km supply radius and 0.2 Mt/a biosynfuel output delivered directly with biomass causes a local traffic density which is already at the limits of acceptability for a densely populated EU area. Truck delivery during 12-hour daylight, 250 days per year excluding weekends and public holidays amounts to 3000 h/a with ca. 20 trucks per hour loaded with 100 m³ (15 t) square straw bales. Together with the empty trucks driving back, this is one truck every 1.5 minutes. This is not a desirable option.

On the other hand, delivery of compact biosyncrudes by rail is also possible overnight and during weekends without harming people. A 1 Mt/a biosynfuel plant consumes about 600 t/h of biosyncrude or the capacity of about two unit trains per hour. Quick syncrude unloading of several hundred m³/h can be achieved rapidly from silo rail wagons by gravity discharge into large appropriate mixer vessels below. Biosyncrude unloading with screw or other pump types takes much time and money; gravity unloading of silo tanks is more convenient and the high biosyncrude transfer rates of about 10 t/min in a large central plant requires at least two transfer stations. Preparation of a free-flowing feed-slurry with the desired composition for the gasifier involves blending delivery batches in large mixing vessels to a constant quality and will be accompanied by heating and better homogenization in a colloid mixer immediately prior to feeding. These final biosyncrude preparation operations

are better performed only once at the gasifier site, not many times in every decentralized FP plant.

Different BTL-plant configurations

In principle, biomass liquefaction by FP and biosyncrude production can also be directly integrated at the site of the large central biosynfuel plant. Major disadvantages of this integrated plant configuration are the high traffic density and the high transport costs for a bulky biomass like straw; this restricts the plant input capacity to values of about < 1 GW or ca. < 100 km transport distance for the typical biomass production densities in the central EU. An advantage of integrated pretreatment is that the inevitable low temperature waste heat in the large plant can be used for reducing a high moisture content of biomass especially of fresh wood with ca. 50%wt.

In Fig. 5, a small 0.5 GW integrated plant with ca. 0.2 Gt annual motor fuel capacity is shown and compared with two potential configurations for 10-times-larger and therefore more economic central biosynfuel plants. The central 5 GWt plants (ca. 4.5 GW biosyncrude input) are assumed to be supplied with biosyncrudes from ca. 50 regional 0.1 GW FP plants via electric rail transport.

Not all farmers or agricultural cooperatives will agree in delivery contracts for their residual straw or wood. The FP

plant distribution will therefore probably not include all neighboring supply areas as shown on the left-hand side in Fig. 5. A more scattered plant distribution with larger or smaller gaps as shown on the right-hand side is a more likely situation. This causes a significant increase of the biosyncrude transport distance, but results in more supply flexibility and security. Biosyncrude transportation costs by rail do not change much with distance (Fig. 3), however, and rail transport will be favored for this kind of plant configuration.

Methodology of cost estimate

This cost estimation follows standard procedures described in textbooks.^{7,10} A relatively simple method for the estimation of manufacturing costs is described in Onken and Behr⁷ and outlined in Table 2. Main cost contributors are usually raw materials and capex. Costs for energy import, labor and generalia are in most cases minor items, especially in large plants.

The estimate of capital investment is based on the method of 'Percentage of delivered purchased equipment cost' and outlined in Table 3. To the delivered purchased equipment cost, E , additional contributions (f_n) have to be added, resulting in direct and indirect costs of ca. 425% as an average value by reported experience. TCI is the sum of direct and indirect costs (= fixed capital investment, FCI)

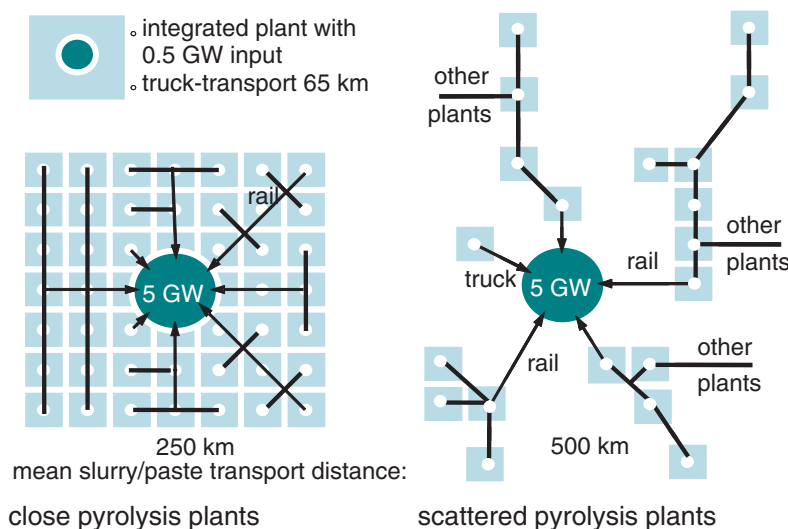


Figure 5. Schematic of integrated BTL plant (upper part left hand side) and BTL plant configurations with close and scattered FP plants.

Table 2. Estimate of total production costs.

1. Materials:	biomass feedstock, technical oxygen, catalysts, etc. (f.o.b. at plant gate)
2. Utilities:	Electricity, high pressure steam, process heat, cooling water etc. Total consumption of own energy production in a self-sustained process is assumed, therefore no credit for heat, high p – steam and electricity export. Technical interrelations between fuel and energy production yields are rather complex and have not been elaborated in detail.
3. Labor and related costs:	wages, salaries and overhead costs
4. Capital and related costs:	average ca. 25% of TCI per year
Depreciation	10 (in a 10-year period)
Interest	6±1
Maintenance and repair	3–6%
Taxes and insurance	2–3%
Plant overhead costs	2±1%
5. Generalia:	Typically 2 – 10% from 1+2+3+4, here ca. 4 % per year R+D, administrative, distribution, marketing expenses etc.

Table 3. Estimate of total capital investment.

$$\text{Total capital investment cost TCI} = E \cdot \Sigma (1 + f_1 + f_2 + \dots + f_n)$$

E = delivered purchased equipment cost 100 % (f.o.b.)

f_i = multiplying factors for piping, electrical, indirect costs, etc.

Direct costs	300 %:	Equipment installation, piping, instrumentation and control, electrical systems, building-yard land, service facilities etc.
Indirect costs ca.	125 %:	Engineering and supervision, construction expenses, legal expenses, contractors fee, contingency etc.
TCI ca.	500 %	fixed capital investment cost, FCI, ca 425 % plus 75 % working capital

plus the working capital, usually about 15% of TCI. A crude TCI estimate for FP- and BTL-type chemical facilities is 5 times the f.o.b. (free on board) equipment cost. The factor of 5 is an average from practical experience with many facilities.

Mass and energy balances

Mass and energy balances are an indispensable basis for plant investment or manufacturing cost estimates. First, the total biomass conversion chain has been translated into a sequence of successive, empirical but stoichiometrically coherent chemical equations, consistent with literature and our own chemical experience. All equations are based on a lignocellulosic starting material with the formula unit C₆H₉O₄, molecular mass (m) = 145 kg, HHV 2923 MJ. In

practice, the moisture and ash content as well as a small amount of heteroatoms (N) have to be added.

The empirical stoichiometry equations (Table 4) allow for the prediction of the mass and energy balance. Successive mass streams are: 7 t airdry straw (15 % H₂O, LHV 4 kWh/kg) → 6 t dry straw → ca. 4.7 t biosyncrude or paste (LHV ca. 5.4 kWh/kg) → 1.25 t FT raw product (LHV ca. 12 kWh/kg) → 1 t biosynfuel (LHV 12 kWh/kg). The reaction enthalpy and the energy balance are obtained from the HHV's of the individual reactants, which are either known or estimated with the Channiwala equation.¹¹ A reaction enthalpy estimate based exclusively on the linear Channiwala equation would always result in zero! A non-zero reaction heat is only obtained with experimental HHV's especially for molecules like CO₂ or H₂O. With the experimentally known

Table 4. Stoichiometric reaction equations for the successive conversion steps of straw into biosynfuel (e: energy fraction; m: mass fraction; mu: formula mass unit/kg).				
feedstock airdry straw: HHV 2923 MJ/mu=186 kg	$C_6H_9O_4$ (ligno-cellulose) m=78%, e=100%	+ 12 g ash m=6.5%	+ 1 g heteroatoms m=0.5%	+ 28 g water m=15%
Channiwala equation: HHV MJ/mu = 349.1 C + 1178.3 H - 103.4 O - 15.1 N + 100.5 S - 21.1 ash, CHONS mass%				
fast pyrolysis: ($C_6H_9O_4$ + 12 g ash + 1 g het)	$\xrightarrow{500^\circ C}$	($C_{2.25}H_{2.2}O_{0.35}$ + 12 g ash) + $C_{2.75}H_{3.2}O_{0.75}$ + 1 g het.	+ 1.55 (H_2O) _l	+ $C_1H_{0.5}O_{1.35}$
dry ligno-cellulose m=85, e=100%		char + ash m=25%, e=39%	organic liquids m=26%, e=48%	reaction water m=15%, e=0%
				gas (sum) m=18%, e=8%
straw biosyncrude				
slurry gasification: (400→1500 K)	($C_5H_{5.4}O_{1.1}$ + 12 g ash + 1 g het + 1.55 H_2O) + 2.1 (O_2 + 0.05 N_2)	$\xrightarrow{1200^\circ C}$	4.3 CO + 3.1 H ₂ + 0.7 CO ₂ + 1.15 (H_2O) _g + 0.14 N_2 + slag	$\Delta H = -453$ MJ/mu; e=15.5%
straw biosyncrude m=66.6%, e=87.5%	technical oxygen m=38%, e=0.36		9.4 mole raw syngas, 7.4 mole CO + H ₂ m=98%, e=72%	slag m=6.5%
wet raw syngas				
CO-shift and syngas cleaning:	(4.3 CO + 3.1 H ₂ + 0.7 CO ₂ + 0.14 N_2) + (1.15 + 1.68) H_2O	$\xrightarrow[\text{catalyst}]{ca. 450^\circ C}$	(2.47 CO + 4.93 H ₂ + 0.14 N_2) + 2.53 CO ₂ + 1 (H_2O) _g + impurities	$\Delta H = -75$ MJ/mu; e=2.6%
dry raw syngas plus 1.68 mole H_2O recycled from FTS			clean conditioned syngas, high boilers + trace impurities removed m=44.6%, e=72%	
FT-synthesis: (low T FTS with Co-catalyst in slurry reactor)	(2.47 CO + 2.2.465 H ₂ + 0.14 N_2)	$\xrightarrow[96\% \text{ conversion}]{\sim 200^\circ C, Co-catalyst}$	2.37 (-CH ₂ -) + (0.7 + 1.68) (H_2O) _g + 0.1 CO + 0.2 H ₂ + 0.14 N_2	$\Delta H = -475.5$ MJ/mu; e=16.3%
clean conditioned syngas	FT raw product m=18%, e=53%	waste water m=23%, e=0%	residual syngas m=3.8%, e=3.4%	

pyrolysis product gas composition a slightly exothermal FP reaction is predicted. But the total pyrolysis process needs some net heat, because the reaction enthalpy of FP is not sufficient to heat up the products to 500°C final pyrolysis temperature.¹² It has been confirmed by own measurements, that 0.8–1.6 MJ/kg dry lignocellulose are required, equivalent to 5–9 % of the initial bioenergy.¹³ The prediction of the product distribution of pressurized entrained flow gasification is simpler. Because of the high gasification temperature above 1200°C, the thermodynamic equilibrium of the homogeneous shift reaction $CO + H_2O \rightleftharpoons CO_2 + H_2$; is approximately attained.

The decreasing chemical energy content in the successive product chain is depicted in Fig. 6. Under favorable conditions, about 45% of the initial bioenergy is converted to the final FT synfuel. The final value depends much on the extent of by-product use either for recycling or combustion for energy generation. The optimum choice between the two options should result in a self-sustained process. Thermal insulation losses shown on the left-hand side, amount to only a few percent in large facilities. A considerable part of ca. 40% of bioenergy is obtained in the form of reaction heat

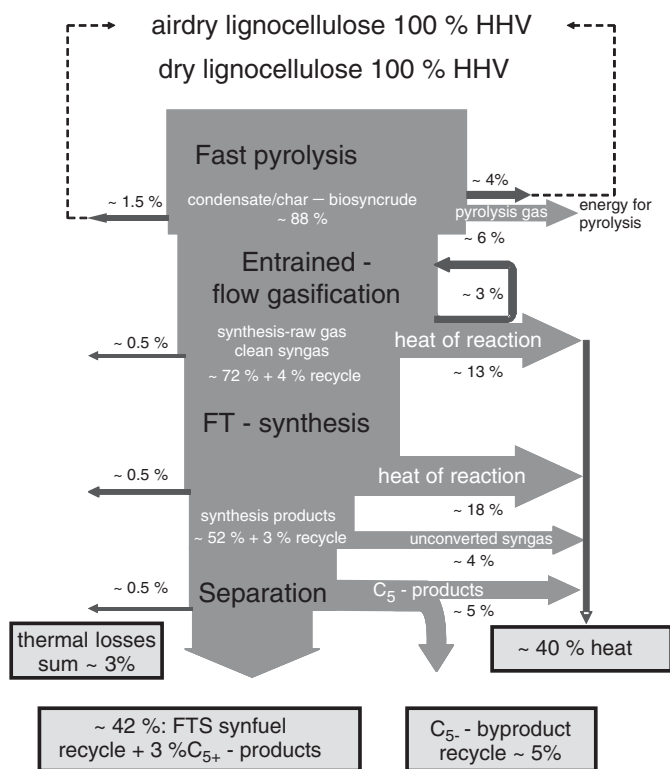


Figure 6. Energy flow in the bioliq® process based on the stoichiometric reaction equations (Table 4).

and sensible heat of the products and can be converted into electricity, high-pressure steam or heat for use in the own process or for export with credit. The less valuable chemical $< C_5$ side products can be used for this purpose by combustion, too. There is also the possibility of byproduct (ca. $5\% < C_5$) recycling via gasification to increase the final main product yield. For the present study we assume complete own consumption of energy without credits for export. The air separation unit (ASU) is the main electricity consumer (ca. $0.45 \text{ kWh}(\text{el})$ per $\text{Nm}^3 \text{ O}_2$).

Fast pyrolysis reference plants

For economic reasons, all plants should be as large as reasonably possible. The usual cost depression exponent of ca. 0.7 for this type of plant results in a specific cost reduction of a factor of 2 for a capacity increase by a factor of 10.

A reasonable maximum transport distance is 30 km for tractor transport by the local farmers and is sufficient for an FP plant with a capacity of 0.2 Gt/a air-dry lignocellulose. For this 0.1 GW input FP plant, €20 million TCI is in the typical range expected from literature data and own estimates. For the very first FP plant, a TCI up to €30 million might be possible.^{14–16} A good estimate for all capital and capital-related expenses is 25% of TCI using a depreciation period of 10 years. For a depreciation period of 20 years, capital related expenses would be reduced to only 20% TCI per year. Average salaries of €60 000 per person per year are assumed including overheads; the estimated number of personnel is scaled with a depression exponent of 0.3.

TCI of FP plants has been estimated by a number of authors.^{14–17} The scatter in these references is large and does not allow a reliable selection of a superior technology. There is not sufficient experience available with large commercial FP plants; even most pilot facilities are scarcely operated or are even decommissioned.

TCI for FP plants already includes cost savings by learning from operating experience and successive plant erection in the convoy mode. According to the comments in the introduction, a TCI near the expected minimum of the learning curve or about two-thirds of the estimated first plant costs have been taken for the following cost calculation.

Cost contributions from biofeedstock and technical oxygen, biomass transport, processing and personnel for the production of 1 t BTL biosynfuel are summarized in Fig. 7 with some additional explanation. Cost contributions by generalia and utilities are small in a self-sustained process and have been neglected in this estimate. The main contributions to the biosyncrude manufacturing costs are shown as a function of plant capacity.

- (1) The cost of air-dry biomass of €45/t in the field plus €18/t for 30 km tractor transport is a reasonable cost assumption in central EU.
- (2) Technical costs in the pyrolysis plant are scaled with a depression exponent of 0.7. The electricity consumed in the pyrolysis plant mainly for biomass diminution is assumed to be delivered from the surplus in the central BTL plant via the grid. Because of the self-supply assumed for the overall process, no energy costs are considered and utility cost contributions are set to zero.

Biosyncrudes from dry lignocellulosics have manufacturing costs about €140/t; about two-thirds are feedstock costs. On an energy basis, this is about equivalent to a crude oil price of ca. €50/bbl. In the future, the biosyncrude manufacturing costs are expected to be compensated at least partly by the recovery of only few percentages of valuable (few €/kg) pyrolysis products.¹⁸ A number of recovery options are already under development.

Large, central biosynfuel plant

A biosynfuel production of $\geq 1 \text{ Mt/a}$ in the form of FT raw product is assumed to be a reasonably economic plant capacity. Such a large BTL complex requires several 100 man-years of detailed engineering. A cost estimate based on a preliminary plant design with only $\pm 20\text{--}30\%$ accuracy based on the methodology described before is already a financial effort corresponding to about a permille of TCI, which is beyond our capabilities. Yet, information on the required investment is indispensable even in an early stage and must be obtained with little knowledge and money. We have used specific costs in US\$ per bbl · d for large GTL plants reported in the internet and the literature.¹⁹ The particular data basis is the newest 35 000 bbl per day Oryx-1 GTL plant in Qatar,

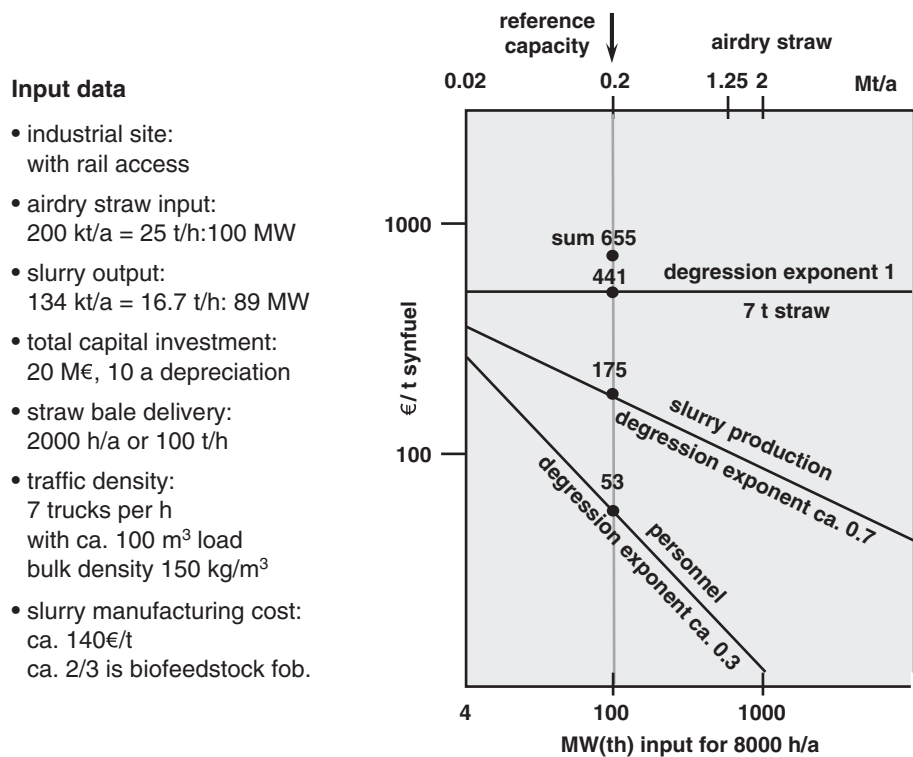


Figure 7. Cost contributions from fast pyrolysis.

Production cost share for 1 ton biosynfuel:		€/t
– Materials: airdry straw bales	7 t · 45 €/t	= 315
Capital and related costs (ISBL):		
– 30 km tractor transport of bales	7 t · 18 €/t	= 126
– Biosyncrude production by pyrolysis	4.7 t · 37.3 €/t	= 175
– Labour : personnel 25 persons à 60 k€/a		= 53
4.7 t biosyncrude for 1 t biosynfuel:		sum = 669

erected by Sasol-QP at a brown-field site with a total capital investment of \$1.1 billion, assumed to be equivalent to €1 million. Scaling down to 1 Mt/a or 24 000 bbl/d with a cost degression exponent of 0.7 gives €0.75 billion of TCI in our case without a separate ASU. Based on that information, the results as shown in Fig. 8 have been derived. Together with an ASU, TCI results in a value slightly above €1 million (see discussion below). Most of the costs related to biomass preparation are already contained in the biosyncrude production facilities. Therefore, adding those to the overall BTL TCI, the resulting TCI would be doubled (Fig. 9). However, most recent information on GTL plants predicts significantly higher costs, also as a consequence of the dramatically increased prices of materials and engineering services.

A BTL plant is more expensive than a GTL plant: about 50% more oxygen is required in the O₂-blown, slagging-entrained flow-gasifier; slag has to be handled and more impurities in the raw syngas must be removed in the gas cleaning system e.g., with a Rectisol-unit. This situation is similar to the front-end in a CTL plant with the exception that most of the feed preparation steps have already been performed in the pyrolysis plants. After production of a clean, conditioned syngas with the desired H₂/CO ratio, the chemical synthesis and raw product work-up steps in the tail-end are practically the same in all XTL-plants.

The large ASU in a BTL plant can be deleted from the investment list, if technical oxygen is supplied over the fence from a separate neighboring ASU and is paid as a raw

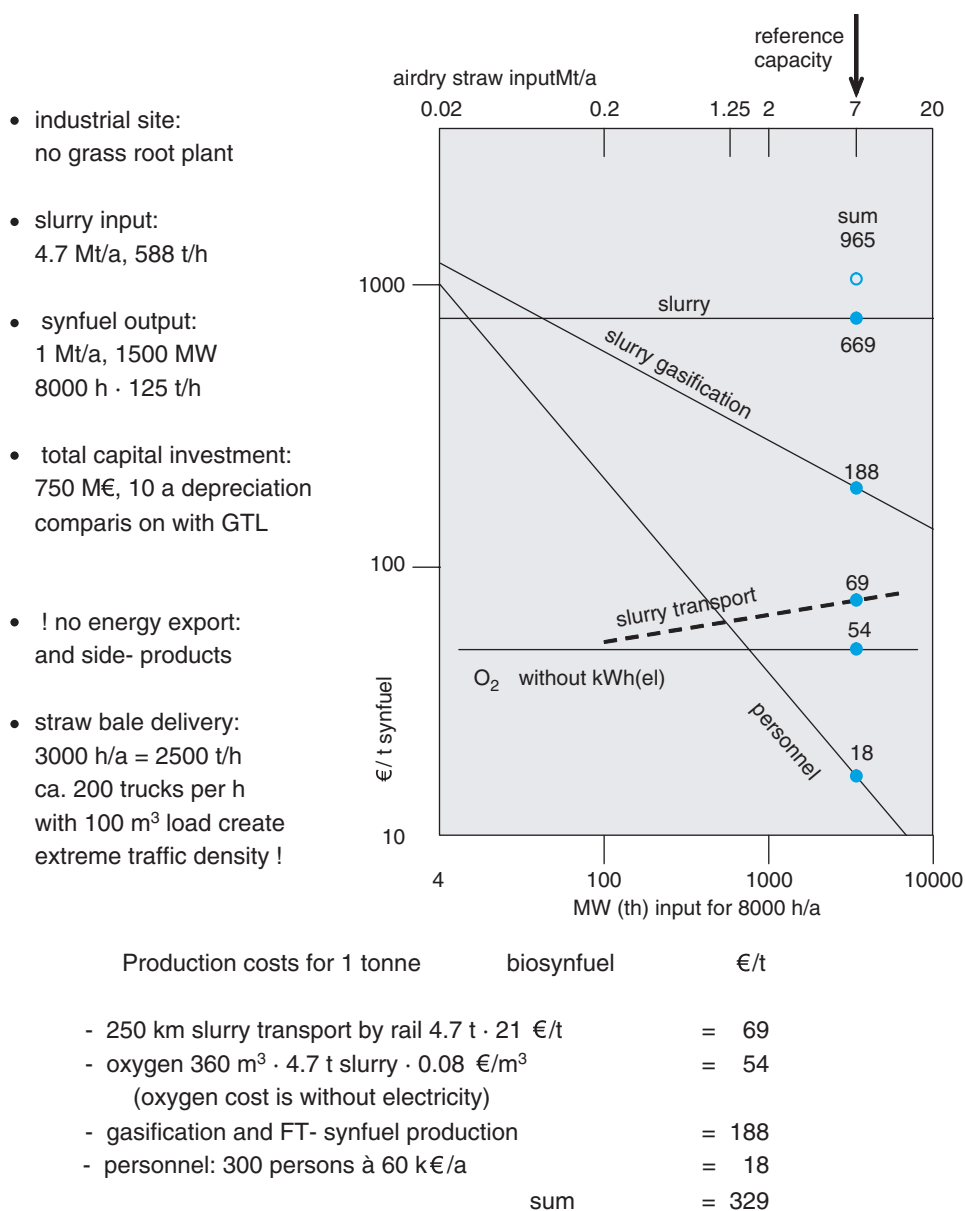


Figure 8. Cost contributions from biosynfuel production.

material in addition to the biomass. When the typical electricity consumption of ca. 0.45 kWh(el) per Nm³ O₂ in the ASU is supplied from the biosynfuel plant as byproduct, the O₂ cost can be reduced to the order of €0.08/Nm³ O₂, since electricity in a large ASU contributes about 60% to the total O₂ production cost.

In the last few years, steel prices and engineering costs have increased considerably, but the over-heated present market situation is not expected to continue forever. On the other hand, the continuing accumulation of operating expe-

rience with GTL and BTL plants will lead to a cost reduction by learning. Further cost reductions are possible with increasing plant size, especially with coal as co-feed.

Synfuel production cost breakdown

The cost breakdown for biosynfuel production with the bioliq[®] process is summarized in Fig. 9. In large BTL plants with a capacity >1 Mt/a, biosynfuel can be produced – including 4% generalia – for about €1.04 per kg or €0.8 per litre. With ±30% estimate error, this is between €0.56 and

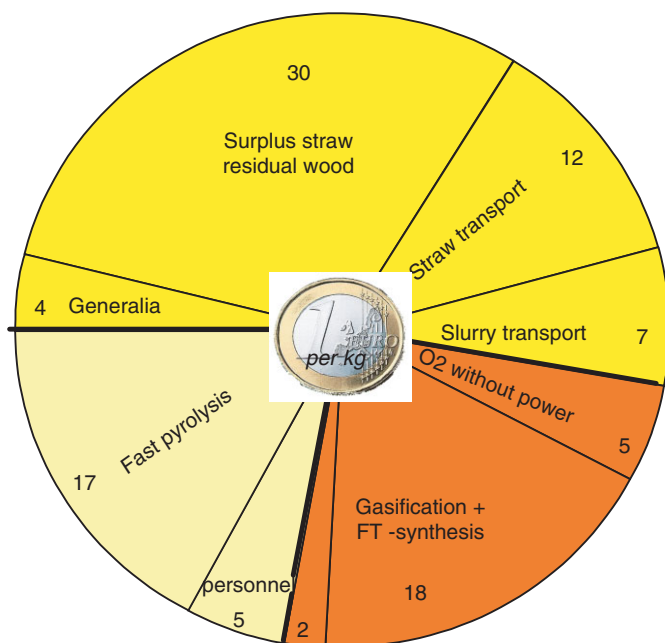


Figure 9. Biosynfuel production cost breakdown % for the Karlsruhe biosyncrude gasification process.

€1.04 per litre. In central EU, the delivered biomass is expensive and contributes about half to the manufacturing costs. Pyrolysis and biosynfuel production technologies share about a quarter each. In many developing countries with low biomass costs, biosynfuel production will be more attractive, and competitiveness with crude oil will be achieved much earlier than in industrialized countries. The development of biomass costs in the future is hard to predict. A crude oil price of \$100/bbl (ca. €75/bbl or €520/t) results in ca. €0.56/l for conventional motor fuel without tax.

Outlook

The energy efficiency of biomass conversion to biosynfuel via syngas as intermediate is only about 40%. A substitution of the present 2008 global motor fuel consumption of 2 Gtoe/a would therefore require a biomass harvest of 4 Gtoe/a. This is four times the present global bioenergy consumption of 1 Gtoe/a and will probably be at the limit of a sustainable level.²⁰ In view of the still-growing motor fuel consumption and many other competitive uses of biomass, a complete substitution of fossil motor fuels by biosynfuel is not only rather unlikely but almost impossible. A sufficient and sustainable long-term supply with liquid hydrocarbon fuels

seems possible only for special applications where liquid fuels are hard to replace e.g., as aviation fuel. This sustainable level probably is less than a quarter of the future transportation energy consumption.

A lack of transportation fuels by exhaustion of the crude oil reserves or a serious shortage by political blackmail will result in a breakdown of the world economy and a considerable risk of armed conflicts. It is therefore likely, that during the inevitable development and transition to new transportation techniques, the still-abundant coal and also natural gas reserves will play an important intermediate role for several decades. Corresponding CTL and GTL technologies for oil substitution are available already today and can be combined with BTL technology in huge and more economic mixed XTL complexes. The growing economy in China, for example, has resulted in the expansion of coal conversion technology via syngas to hydrogen, methanol, DME, and also FT-synfuel; BTL integration is easily possible.

In a BTL plant for methanol or FT-synfuel production, usually less than or optimistically up to about half of the carbon and the bioenergy initially present in the biomass is converted into the final fuel product. In the successive process steps, much carbon is converted into CO₂, mainly via the shift reaction $\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$ which serves to transform CO to H₂ to adjust the required H₂/CO ratio for synfuel production (see reaction equations in Table 4). After the shift reaction, the CO₂ generated can be separated and is recovered in concentrated form under high pressure. The CO₂ absorption/desorption recovery procedure can be easily combined with a final CO₂ disposal, e.g., by pressing CO₂ into a deep underground storage site. If hydrogen is the only desired product, all carbon can be easily separated and disposed of in this way. The combination of syngas technology with a final CO₂ disposal can be a significant contribution to climate protection and environmental compatibility.

In a BTL plant, practically all biocarbon can be converted into biosynfuel in an environmentally safe way, if the required additional H₂ is supplied from other sources, e.g., via coal gasification, and the produced fossil CO₂ is completely disposed of with little additional technical effort. The biosynfuel production can at least be doubled in this way and the huge XTL complex can contribute via the economy of scale. The Karlsruhe bioliq[®] concept is well suited for large XTL concepts with mixed feedstock.

Overall, coal is still a cheaper feedstock than biomass and can contribute significantly and cleanly to a secure supply of transportation fuels, until new transport technologies are introduced into the market. Combined with CO₂ disposal, this is possible without emission of fossil CO₂.

Conclusion

Because of the complex technology to be applied, BTL plants for biosynfuel production can only be economic in large facilities. A reasonable BTL plant capacity is ≥ 1 Mt/a biosynfuel similar to the already-existing commercially operated CTL and GTL plants. In this study on the cost estimate of the bioliq[®] concept, the BTL plant cost estimates have therefore been based on available information on CTL and GTL plants. The bioliq[®] concept consists of a multistep approach: in a first stage of biomass pre-treatment, an energy densification by biomass liquefaction in an FP process generates a compact biosyncrude exhibiting a volumetric energy density more than 10 times higher than that of the original biomass. The densified intermediate product can now be cheaply transported from many local facilities by electric rail over long distances to a large and economic central biosynfuel plant. In addition to the capex for the large and complex central biosynfuel plant, an investment effort of the same order of magnitude is required for the construction of several dozen regional pyrolysis plants. Investment costs estimated for FP plants reported in the literature have been complemented by own studies for plants with ca. 100 MW(th) biomass input. The breakdown of BTL synfuel manufacturing costs of ca. €1/kg in central EU shows, that about half of the costs are caused by the feedstock, including transport. The other half is caused by technical costs, which are about proportional to TCI for the pyrolysis and biosynfuel production plants. The dominant contribution to utilities is due to electricity consumption including oxygen production, requiring about 18% of the biomass energy. This is almost half of the electricity which is produced internally from the waste heat of a self sustained process. Labor is a minor contribution in the relatively large facilities and contributes less than 10% to the manufacturing cost.

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