LIGNOCELLULOSIC BIOREFINERY ECONOMIC EVALUATION

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The production economics of biomass-derived fuels and bio-based chemicals is a major challenge. Furthermore, the raw material, the conversion process and the by-products – all significantly influence the production economics. The large number of alternative production routes and by-products requires a simple approach for estimating production economics. Conclusions on the relative feasibilities of the production routes can be drawn even with limited information on the capital cost for a given technology and with uncertainty regarding the process parameters – such as product yield. In this paper, the relative feasibilities of lignocellulosic biomass upgrading routes for biofuel components and chemicals were studied on the basis of production costs. An economic evaluation method for biorefining of lignocellulosic biomass is presented. The application of the model using hemicellulose or lignin as a raw material for biofuels or chemicals, coupled with high-value fiber use of cellulose, was found as the most feasible production route. Hydrogen production from biomass, coupled with hydrogasification and methanation from forest biomass, appeared feasible due to high energy yield.

Keywords: biorefinery, biofuels, biofuel properties, biomass conversion, lignocellulosic biomass upgrading, optimization model

INTRODUCTION

Lignocellulosic biomass-derived products, such as second generation biofuels, can significantly reduce green house gas emissions, compared to fossil-based products. In addition, the raw material does not compete with food production. Also, many common petrochemicals, such as ethylene, a raw material for petrochemicals, could be obtained with lower green house gas emissions from bio-based feedstocks. The economics of the conversion processes and logistics is a major challenge for lignocellulosic biomass. The maturity of the conversion processes is another challenge, leading to uncertainty in predicting the investment cost for the production plants.

Several studies have presented estimates on biofuel production costs through gasification-based routes to Fischer-Tropsch diesel, dimethylether (DME), methanol and methane,[1,2] fermentation-based routes,[3] and biofuel production through pyrolysis.[4] A comparison of ethanol and gasification-based biofuels has been also performed.[5] The effect of scale, depending on the logistics cost and capital cost, was studied,[6] and the by-product and integration of ethanol production has been discussed.[7] Another option is to treat first the biomass by a pre-treatment method, so as to transport biomass more easily and to increase its heating value. The pre-treatment methods enable the utilization of larger units, and usually increase the efficiency of the subsequent conversion processes. However, the pre-treatment stages increase the cost of the raw material used in subsequent processes. The economics of pre-treatment – including torrefaction, fast pyrolysis and pelletization – has been studied by Uslu *et al*.[8] Furthermore, optimization models have been developed, for maximizing the profit of all products from lignocellulosic biomass, for minimizing the environmental impact, etc. Usually, the model has been linearized to be easily solved by linear programming.[9] Since optimization usually involves many objectives, the solution along the Pareto curve can be employed. It shows the optimal solution when varying the weight of each variable in the objective function.

To the authors' knowledge, no approach similar to that put forward in the paper has been ever presented. The production costs of chemical and fuel components are studied through many alternative routes, by varying process and economic parameters, such as heat consumption, electricity consumption, product yield and investment cost. Instead of calculating a particular case with certain values of the parameters, a large range of parameters can be studied, to determine which route is optimal. Even with limited information on the parameters, a comparison of the production route economic feasibilities can be done. Some parameters affect the economics more than others, and reasonable economic evaluation can be done even with rough estimates of the less important parameters.

For gasification, the experimental results differ significantly from the gas composition values predicted by models. The gasification yields do not depend only on the process conditions, but also on the gasifier dimensions – as chemical equilibrium is not reached. A comparison of estimated *vs*. pilot scale results has been done earlier.[10] Furthermore, selectivity in subsequent chemical synthesis stages, such as Fischer-Tropsch, also depends on the process conditions: catalyst, rector dimensions, etc. The fermentation or sugar utilization routes are affected by the yield of hydrolysis performed with chemicals or enzymes. Furthermore, the yield of fermentation, often expressed as percentage of the theoretical yield, is equally important. For biomass pyrolysis, the yield of pyrolysis oil depends on both raw material, reaction conditions, etc. Also, the selectivity of hydrogenation into traffic fuels has significant effects on the production cost.

METHODS

Multiple production routes for lignocellulosic biomass production were evaluated, from an economic perspective, by a three-stage approach. The aim was to find the production route with the minimum production cost for a biofuel or a chemical, for each raw material, when the process and the economic parameters occur in a known range. For biofuel components, certain requirements on product quality should be necessarily fulfilled.

Firstly, the material yield and heat content of the main product were calculated according to an approach described elsewhere.[11] The heat of reaction during conversion can be calculated as the difference of the higher heating values of products. For a conversion process releasing heat, it can be used for generating steam. When heat is needed, the ideal heat demand can be calculated as the difference of the higher heating values of products. In this stage, a fixed price per energy unit was assumed for both utilities, while the temperature level of heat was not taken into account. Firstly, the raw material cost necessary to produce 1 MWh of component used as a biofuel was considered. The raw material costs were calculated per 1 ton of chemical. When hydrogen was needed in the hydrogenation of sugars, it was assumed to be generated by gasification of lignin and extractives, with 75% efficiency on lower heating values. Such an efficiency value was calculated as the maximum theoretical efficiency in pine lignin gasification. : When heat is needed in a reaction, it was assumed to be supplied by heat recovered from hot synthesis gas. The revenue of by-products, such as lignin or generated steam, was subtracted from the production cost. This gives the minimum possible production cost from a given raw material to a product, as shown by Eq. 1, where $C_{p,\,min}$ equals the minimum production cost of a production route for a main product, $C_{biomass}$ is the cost of biomass per energy unit, $C_{byproduct}$ is the revenue from by-products, η is equal to the yield of product in the ideal case (in energy units for biofuels and tons for chemicals). When the utilization of the product favors an external process, the benefit can be treated as by-product revenue – C_{ext}. For example, in some cases, the extraction of lignin from a pulping process can increase the pulp mill capacity with the existing equipment:

$$C_{p,\min} = \frac{C_{biomass} - C_{byproduct} - C_{ext}}{\eta_{ideal,product}} \quad (1)$$

If the production cost for a biofuel component is known, the production route with higher cost per energy unit (compared to that of the reference route), can be discarded in this stage. When producing a biofuel component at a low yield, the raw material cost might exceed the production cost of another production route, even if the value of the by-product, such as steam, has been subtracted from the production costs.

In the following stage, the production costs are calculated for the ideal case of the highest theoretical yield for all primary conversion steps and all subsequent chemical reactions. Both operating and investment costs are included. The costs considered are described in Eq. 2. The additional costs on top the minimum production cost include: process heat consumption cost – $C_{heat,co}$, electricity consumption cost in the process – C_{el}, cost of chemicals – Cc_{hem}, cost of enzymes – $C_{enzymes}$, additional costs, such as water treatment, logistics cost, etc. – C_{add}. The logistics cost can be included in calculation by assuming a fixed yield per collection area or by using biomass availability charts for a collection area assumed to be a circle. Subsequently, the area required for the given plant capacity can be determined and the collection distance can be calculated by assuming that the distance of biomass transportation is equal to the radius of the collection area. Since the biomass transport on roads is not usually the shortest distance, this assumption is commonly used.[6] Furthermore, the transport cost for each type of transport can be calculated by correlations based on cost per km, or by more rigorous calculations, including the capacity of the transport vehicle, etc.

In the capital cost, $C_{capital,\ ref}$ refers to the capital cost for a reference plant with a known capacity. F_{plant} is the calculated capacity of the plant and F_{ref} is the reference plant capacity. O_{annual} represents the annual hours of operation, and a_f is the annuity factor depending on the required profit rate for the capital invested in the process and the lifetime of the investment. C_{fixed} is the additional fixed cost, such as labor, maintenance, etc., per year.

$M_{biomass}$ is the duty of biomass feed in MW, on lower heating value (LHV) basis, and $Q_{biomass}$ is the duty of the biomass feed in MWh on LHV basis for 1 ton of oven dry biomass.

For the gasification reaction, 100% selectivity means a maximum yield of hydrogen and carbon monoxide, to be estimated by equilibrium models. For hydrolysis, 100% selectivity means that all sugars are completely hydrolyzed. For pyrolysis, the heat content of pyrolysis oil and by-products equals the heat content of the original biomass, since there is no heat exchange with the environment. The higher heating value is assumed to agree with the experimental data, meaning that the energy in biomass is converted into pyrolysis oil, which is more energy dense:

$$C_{additional} = C_{heat,co} + C_{El} + C_{Chem} + C_{enzymes} + C_{add} + \frac{C_{capital,ref}\left(\frac{F_{plant}}{F_{ref}}\right)^{0.7} a_f + C_{fixed}}{O_{annual} M_{biomass,F} / Q_{biomass}} \quad (2)$$

The feasibility of a route can be first evaluated from the literature values given for these parameters. Subsequently, the required values for the parameters of other routes, resulting in lower production costs, can be calculated. Other alternatives can be discarded.

A significant variable is the electricity needed for, *e.g.* compressing the synthesis gas to the required pressure, manufacturing the oxygen used as a gasification agent and cutting biomass into pieces. Another variable is the heat used for the separation of products by distillation, drying of the feedstock before gasification, etc. Both electricity and heat usage costs can be expressed per ton of dry raw material. The cost of enzymes and the additional costs, such as the water treatment costs, can also be expressed as costs per ton of dry raw material.

Also, the effect of the capital cost is determined. For a certain fixed capital investment, the annual payment is calculated on the basis of the lifetime of the investment and of the required profit rate of the capital. When the investment period is over, the residual value of the plant is assumed to be 0. The influence of the production plant scale was estimated by scaling the investment cost by a capacity exponent of 0.7.

In the present paper, the additional costs are calculated for the typical minimum, normal and maximum values shown in Figure 1 and Table 3, on assuming that, for all studied processes, the parameters are in the shown range. The enzyme costs naturally apply only for the hydrolysis platform production routes. The minimum, normal and maximum values were estimated from literature data for biorefinery processes.[1,3] The values are rough estimates that demonstrate the significance of the different variables for the total production cost of a substance.

In the final stage, the effect of selectivities on the conversion processes is determined. According to Eq. 3, C_{total} is the total production cost for 1 ton of biomass. η_{ideal} is the ideal yield of the reaction sequence – as in Eq. 1, Z_{total} is the selectivity of the total reaction sequence. For many consecutive reactions, total selectivity is the product of all selectivities for each reaction. When selectivity is less than 1, it is assumed that the by-product exhibits only heating value and that it is combusted. Therefore, an additional income is obtained from the by-products, to be calculated as the difference as the difference of the ideal lower heating value, LHVideal, of the component and the real heating value expressed with selectivity. C_{heat} refers to the value of heat obtained as a by-product, as €/MWh and $C_{raw,\ material}$ is the value of the biomass based on energy content, as €/MWh:

$$P_{Prod,real} = \frac{C_{total}}{\eta_{ideal} z_{total}} - LHV_{ideal}(1 - Z_{total})\frac{C_{heat}}{C_{raw,material}} \quad (3)$$

The total cost from the previous stage, including operating and investment costs, is calculated per energy unit of fuel or ton of chemical. The effects of the production route ideal energy efficiencies and selectivities are shown in Figure 2 and Table 4.

The objective in view was a synthetic economic evaluation of each process and raw material, on the basis of selectivity data available in literature.

In the calculation, an electricity price of 40 €/MWh is used. Heat value is assumed to be of 13 €/MWh, at all temperature levels, the cost of by-product acetone is of 700 €/ton, lignin for high-value application – 400 €/ton, cellulose to specialty fiber application – 500 €/ton, and biogas or hydrogen containing fermentation gas from butanol production – 40 €/MWh. When biogas is produced as the main product, the production cost is calculated and no fixed price of biogas production is assumed.

The process routes described earlier[11] did not include hydrogasification, formic acid production, methylformate and combined heat and power (CHP) electricity production. In the hydrogasification process, hydrogen (100 kg/h per dry ton of biomass) is produced by gasification-based hydrogen production from biomass. Biomass is fed at a 15 wt% moisture content on total basis, simultaneously with 300 kg/h per ton of dry biomass 500 °C steam. Gasification is carried out at 30 bar. In CHP production, an efficiency of 35% to electricity is assumed. Formic acid production is described by Eqs. 4 and 5:

$$2CO + 2H_2 \rightarrow HCOOCH_3 \quad (4)$$

$$HCOOCH_3 + H_2O \leftrightarrow HCOOH + CH_3OH \quad (5)$$

For the synthesis gas platform, the new production routes considered are bioethanol production with biogas production from the distillation stillage and isopropanol production from the ketonization of acetic acid, with subsequent dehydrogenation of acetone, as presented in Eqs. 6 and 7:

$$CH_3COOH \rightarrow 2CH_3COCH_3 + CO_2 \quad (6)$$

$$CH_3COCH_3 + H_2 \rightarrow CH_3CH_2OHCH_2 \quad (7)$$

In conversion routes using hydrogen pyrolysis oil upgrading, ethanol production from acetic acid, methyltetrahydrofurane (MTHF) and isopropanol hydrogen is also assumed to be obtained from biomass. In sugar-based based production routes, hydrogen is produced from lignin with energy efficiency calculated for pine lignin given as LHV %. The difference in lignin composition and heating values to other biomass components is assumed to be negligible. For the pyrolysis, the hydrotreating hydrogen is assumed to be produced by gasification of pyrolysis oil itself. Similarly, if a chemical reaction in the conversion route is endothermic – such as in the production of olefins (propylene or ethylene) or in the ketonization of acetic acid – the heat needed is assumed to be produced by combustion of lignin.

RESULTS AND DISCUSSION

Table 1 lists the minimum possible production costs for the thermochemical reaction platform – including gasification-based routes and pyrolysis oil upgrading through hydrodeoxygenation. The minimum production costs are gives in €/MWh for the components that can be used for biofuels, and in €/ton for chemicals, such as ethylene, acetic acid and formic acid.

The minimum production cost is directly related to the energy efficiency of the production route, when the price of raw material per energy unit is equal. This seems logical, since the by-product heat has been assigned to a lower value (13 €/MWh) than the biomass raw material (16 €/MWh). Furthermore, in Table 2, the minimum production costs for the hydrolysis platform are shown. The minimum production costs with negative values are obtained for cellulose production, with hemicellulose obtained as a by-product. Also, lignin utilization gives negative values for the minimum production costs, because no additional costs have been considered, and the revenue from the by-product is significant (high-value lignin or cellulose for fiber application).

It can be seen that, when one biofuel product is ethanol produced from, *e.g.*, C6 sugars, the minimum cost of biofuel production is higher than for synthesis gas-based routes. This is because a smaller part of the biomass is converted into biofuel, and the remaining biomass – lignin, etc. – is assumed to be used for producing energy by combustion. However, when biogas or fermentation gas are produced as by-products, a lower value for the minimum production cost is obtained, due to the higher value (40 €/MWh) of the by-product. A lower minimum production cost is obtained for isopropanol than from the ethanol derived from acetic acid. Also, a higher minimum production cost was obtained for the ethanol obtained from acetic acid or MTHF than from ethanol or ABE fermentation, possibly because of the lower efficiency of hydrogenation.

The additional costs for normal, minimum and maximum cases were calculated and listed in Table 3. With the assumed values on heat, electricity and enzyme costs (hydrolysis platform routes), the significant costs are capital costs and raw material costs.

Figure 1 presents the results of the calculations. The costs refer to 1 ton of dry biomass produced.

The different production costs per energy unit of biofuel or chemical substance are calculated for different energy yields of the conversion route. Also, deviations from the ideal yields are shown in Table 4 and Figure 2. It can be seen that the energy yield has a very significant influence on the production economics. Also, the tradeoff between yield and the capital cost can be assessed by comparing the results in Tables 3 and 4.

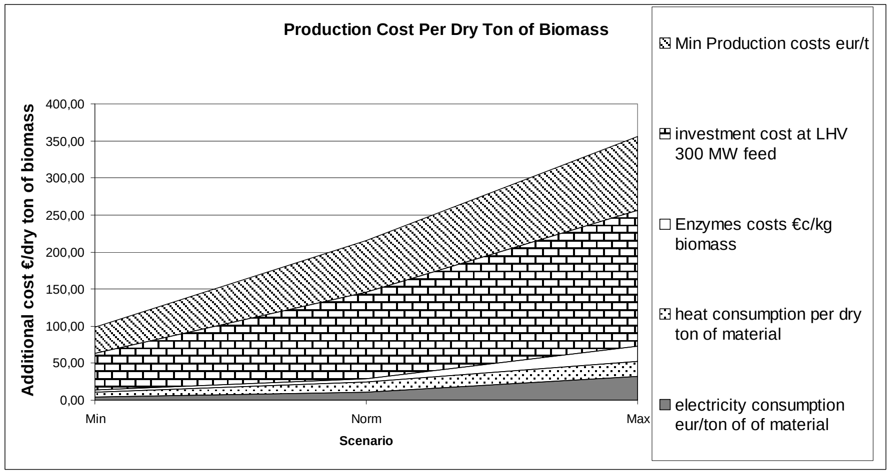

Figure 1: Cost of biomass conversion for minimum, normal and maximum cases

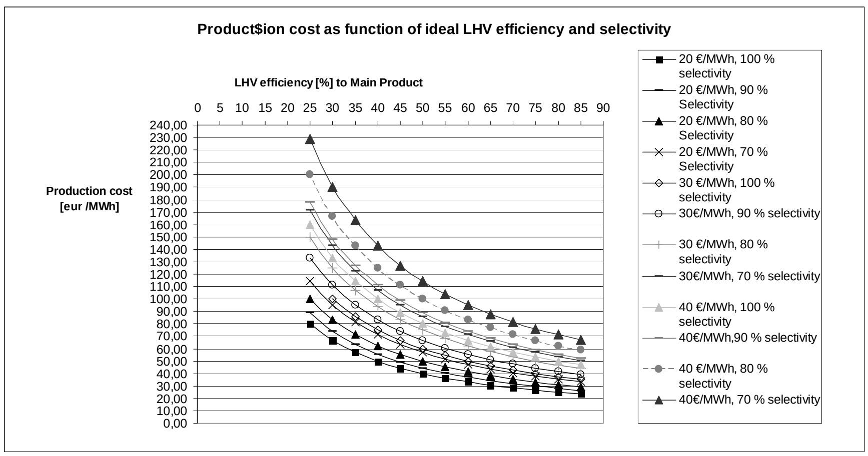

Figure 2: Production cost as a function of main product energy content LHV % of raw material and selectivity for the main product compared to ideal yield

CONCLUSIONS

A model was developed for assessing the profitability of biomass refining. The model was applied to calculate the minimum production cost and to assess the influence of various parameters – such as electricity and heat consumption, chemicals, logistics and capital costs, and product yields.

The maximum sales income from biomass and the minimum production cost were obtained using cellulose for fiber production, and hemicellulose for biofuel or chemical production. Even lower production cost could be achieved by using lignin for high-value applications or by converting it into biofuels.

When all by-products are used for energy production with lower value than that of the raw material, the minimum production costs were obtained for gasification-based routes, as due to the higher yield of the main product. However with higher value for by-product ethanol coupled with biogas production and acetone-butanol-ethanol fermentation appears as more feasible. For the gasification-based route, hydrogasification with subsequent methanisation gave low minimum production costs, as due to the high energy yield. The total product value of the gasification-based routes could be increased by co-production of high oxygen content chemicals (such as acetic acid and formic acid), for which the sales value is higher per energy content than that for fuels.

For hemicelluloses, the route using both C5 and C6 is the most profitable. Either ABE fermentation or acetic acid fermentation, or ethanol fermentation coupled with biogas production could be used.

Table 1
Thermochemical conversion routes: raw material cost, raw material cost after subtraction of by-product income and minimum production cost (in €/MWh for substance and €/ton for chemicals)

Thermal platform	Raw material/Species								
	Domestic softwood in Finland		Domestic hardwood in Finland			Foreign trees		Non-wood biomass	
	Pine	Spruce	Black Alder	Aspen	Silver Birch	Eucalyptus	Larch	Sugar Cane Bagasse	Wheat Straw
Syngas									
Raw material cost, €/MWh (LHV) raw material	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Raw material cost, €/dry ton raw material	85.8	84.7	84.0	83.1	82.8	85.2	80.9	71.9	73.1
By-products heat, €/dry ton raw material	9.63	10.36	13.01	13.39	14.39	14.34	14.52	15.14	13.35
Operating by-products, €/dry ton raw material	76.2	74.3	71.0	69.7	68.4	70.9	66.3	56.8	59.7
Min. operation costs, €/MWh (LHV) main product	16.9	17.0	17.2	17.2	17.3	17.2	17.1	17.3	17.3
Hydrogen production									
By-products revenue, €/dry ton raw material	9.3	10.1	12.7	13.1	14.1	14.0	14.3	14.9	13.1
Operating by-products, €/dry ton raw material	76.5	74.6	71.3	70.0	68.6	71.2	66.6	57.0	59.9
Min. operation costs, €/MWh (LHV) main product	18.1	18.1	18.4	18.3	18.5	18.5	18.2	18.4	18.4
Methanol synthesis									
By-products heat, €/dry ton raw material	16.5	17.1	19.3	19.6	20.5	20.6	20.5	20.2	18.7
Operating by-products, €/dry ton raw material	69.3	67.6	64.7	63.5	62.3	64.6	60.4	51.7	54.4
Min. operation costs, €/MWh (LHV) main product	17.6	17.7	18.0	17.8	18.0	18.0	17.8	17.9	17.9
Hydrogasification									
By-products revenue, €/dry ton raw material	10.8	10.6	16.0	17.7	17.8	16.0	11.5	13.2	10.1
Operating by-products, €/dry ton raw material	75.0	74.1	68.0	65.4	64.9	69.2	69.4	58.7	63.0
Min. operation costs, €/MWh (LHV) main product	17.0	17.3	17.6	17.6	17.8	17.5	18.6	19.0	20.2
DME synthesis									
By-products heat, €/dry ton raw material	19.2	19.6	21.7	22.0	22.8	23.0	22.7	22.1	20.7
Operating by-products, €/dry ton raw material	66.7	65.0	62.3	61.1	60.0	62.2	58.1	49.8	52.4
Min. operation costs, €/MWh (LHV) main product	17.2	17.3	17.6	17.5	17.7	17.7	17.4	17.6	17.6
Formic acid by methyl formiate									
Heat value, €/dry ton raw material	59.6	52.5	58.6	59.3	58.7	58.3	57.9	52.1	52.4
By-products revenue, €/dry ton raw material	26.2	32.2	25.4	23.8	24.1	26.9	23.0	19.8	20.6
Min. operation costs, €/ton main product	32.5	28.4	34.2	34.5	35.1	33.1	33.8	34.9	35.2

Ethanol by methanol carbonisation									
By-products revenue, €/dry ton raw material	21.0	21.4	23.4	23.7	24.4	24.7	24.4	23.5	22.1
Operating by-products, €/dry ton raw material	64.8	63.2	60.6	59.4	58.4	60.5	56.5	48.4	50.9
Min. operation costs, €/MWh (LHV) main product	17.4	17.5	17.8	17.7	17.9	17.9	17.6	17.8	17.8
Acetic acid from methanol									
By-products revenue, €/dry ton raw material	29.6	30.6	31.3	31.5	32.0	32.5	31.8	29.8	28.8
Operating by-products, €/dry ton raw material	56.2	54.1	52.7	51.6	50.8	52.7	49.1	42.1	44.3
Min. operation costs, €/ton main product	59.5	60.0	61.0	60.4	61.2	61.3	60.2	60.9	60.9
MTO process from methanol									
By-products revenue, €/dry ton raw material	21.7	22.1	24.0	24.3	25.0	25.3	24.9	24.0	22.6
Operating by-products, €/dry ton raw material	64.1	62.6	60.0	58.8	57.8	59.9	55.9	47.9	50.4
Min. operation costs, €/ton main product	218.0	219.0	222.8	221.1	223.7	223.8	220.4	222.7	222.7
n-Propanol and ethanol through hydration of olefins									
By-products revenue, €/dry ton raw material	22.2	23.5	24.5	24.8	25.5	25.8	25.4	24.4	23.1
Operating by-product, €/dry ton raw material	63.6	61.2	59.5	58.3	57.3	59.4	55.4	47.5	50.0
Min. operation costs, €/MWh (LHV) main product	17.6	17.7	18.0	17.8	18.0	18.0	17.8	17.9	17.9
Methanisation of Syngas									
By-products revenue, €/dry ton raw material	23.8	24.2	26.0	26.2	26.9	27.2	26.8	25.5	24.3
Operating by-products, €/dry ton raw material	62.0	60.5	58.0	56.9	55.9	58.0	54.1	46.4	48.8
Min. operation costs, €/MWh (LHV) main product	17.7	17.8	18.1	17.9	18.2	18.2	17.9	18.1	18.1
Ft-Diesel once-through at 30 bar									
By-products revenue, €/dry ton raw material	24.9	26.0	26.9	27.2	27.8	28.2	27.7	24.9	26.0
Operating by-products, €/dry ton raw material	61.0	58.7	57.1	55.9	55.0	57.1	53.2	61.0	58.7
Min. operation costs, €/MWh (LHV) main product	17.2	17.3	17.6	17.4	17.7	17.7	17.4	17.2	17.3
CHP 35% efficiency on LHV basis									
District heat., €/dry ton raw material	50.04	49.25	48.41	48.36	47.75	49.07	47.42	42.13	42.46
Operating by-products, €/dry ton raw material	35.8	35.4	35.6	34.7	35.0	36.1	33.4	29.8	30.6
Production costs, €/MWh (LHV) main product	19.1	19.1	19.4	19.1	19.3	19.4	18.9	18.9	19.1
Pyrolysis oil hydrodeoxygenation									
Hydrogen need, €/dry ton raw material	N/A	N/A	N/A	N/A	N/A	N/A	39.78	N/A	N/A
By-products revenue, €/dry ton raw material	N/A	N/A	N/A	N/A	N/A	N/A	14.5	N/A	N/A
Operating by-products, €/dry ton raw material	N/A	N/A	N/A	N/A	N/A	N/A	119.81	N/A	N/A
Min. operation costs, €/MWh (LHV) main product	N/A	N/A	N/A	N/A	N/A	N/A	20.09	N/A	N/A

Table 2
Hydrolysis platform conversion routes: raw material cost, raw material cost after subtraction of by-product income and minimum production cost (in €/MWh for substance and €/ton for chemicals)

Biochemical platform and subsequent upgrading	Raw material/Species								
	Domestic softwood in Finland		Domestic hardwood in Finland			Foreign trees		Non-wood Biomass	
	Pine	Spruce	Black Alder	Aspen	Silver Birch	Eucalyptus	Larch	Bagasse	Wheat Straw
All C5 and C6 sugars production rest for energy									
Raw material cost, €/MWh	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Raw material cost, €/ton raw material	85.8	85.8	85.8	85.8	85.8	85.8	85.8	85.8	85.8
By-product income, €/ton raw material	36.4	35.3	34.3	34.0	33.3	35.3	32.4	24.6	25.2
Min. operating costs, €/MWh (LHV of product)	18.2	21.4	19.2	18.7	17.2	15.8	18.3	20.1	19.8
Hemicellulose sugars production									
Cellulose to fiber utilization process									
Lignin and rest for energy									
Heat revenue, €/ton raw material	36.7	35.0	29.9	26.6	28.9	35.2	31.7	17.1	35.2
Cellulose by-product income, €/ton raw material	205	219	240	266.5	205	208.5	230	205	150
Min. production costs, €/MWh (LHV of fuel)	-14.7	-17.7	-17.1	-20.0	-9.9	-14.9	-15.6	-9.4	-61.2
C6 sugars for ethanol rest for energy, €/ton raw material	39.2	39.8	45.4	43.2	45.2	39.1	33.4	36.8	36.9
By-products revenue, €/ton raw material	46.6	46.0	40.4	42.6	40.6	46.7	52.4	49.0	49.0
Production cost, €/MWh product	19.0	19.7	21.6	21.3	22.4	19.6	20.3	27.3	26.7
Ethanol (C6 sugars) + other sugars									
Biogas + energy									
Biogas, €/ton raw material	7.9	7.9	27.1	25.5	41.5	27.0	10.6	42.5	42.5
Heat, €/ton raw material	36.4	37.0	35.6	34.0	30.2	29.4	29.5	21.5	21.5
By-products revenue, €/ton raw material	41.5	40.9	23.1	26.3	14.1	29.4	45.7	21.8	21.8
Production cost, €/MWh product	16.9	17.5	12.3	13.1	7.8	12.4	17.7	12.2	11.9
Ethanol + biogas + high-value lignin to high-value use									
High-value lignin, €/ton raw material	135	135	110	81.5	94.5	155	150	75	150
Sugars for biogas, €/ton raw material	7.9	7.9	27.1	25.5	41.5	27.0	10.6	42.5	42.5
Heat, €/ton raw material	16.3	18.0	17.7	16.4	13.3	10.4	13.5	13.3	12.6
Operating by-products, €/ton raw material	-73.4	-75.1	-69.0	-37.5	-63.4	-106.6	-88.3	-44.9	-119.3

Production cost, €/MWh product	-29.9	-32.2	-36.9	-18.7	-34.9	-44.8	-34.2	-25.0	-64.9
Acetone butanol ethanol fermentation									
Fermentation gas, €/ton raw material	17.9	17.0	18.7	19.3	22.2	22.5	19.6	22.3	12.1
Acetone, €/ton raw material	57.1	54.5	52.8	55.0	57.9	63.8	61.0	57.8	41.7
Heat, €/ton raw material	59.5	59.1	57.8	57.0	54.9	55.8	54.3	46.1	52.6
Operating by-products, €/ton raw material	10.8	14.3	14.3	11.6	5.8	-0.5	5.2	5.7	32.0
Min. operating costs, €/MWh product	7.2	10.0	10.3	8.0	3.8	-0.3	3.2	3.8	29.2
Acetic acid fermentation									
By-products revenue, €/ton raw material	11.7	11.8	11.4	11.0	10.0	10.0	10.0	7.6	11.1
Min. operating costs, €/ton product	109.6	114.5	113.1	110.0	102	96.5	104.	105.	152.4
Acetic acid to ethanol									
Energy content in hydrogen, €/ton raw material	23.3	22.3	22.7	23.4	25.5	27.1	25.0	25.6	16.9
By-product heat, €/ton raw material	17.1	18.5	16.5	14.3	8.4	6.7	8.8	11.5	21.0
Ethanol cost, €/MWh product	23.0	23.5	23.7	23.6	23.5	22.9	23.8	22.8	28.2
Isopropanol from acetic acid through acetone hydrogenation									
Heat needed, €/ton raw material	38.5	36.8	37.5	38.7	42.2	44.7	41.3	42.2	27.9
Energy content in hydrogen, €/ton raw material	5.8	5.6	5.7	5.9	6.4	6.8	6.3	6.4	4.2
By-product heat, €/ton raw material	29.5	30.3	28.5	26.7	22.0	21.0	22.1	25.1	30.0
Isopropanol, €/MWh product	19.5	20.1	20.4	20.4	20.2	19.3	20.6	19.2	26.7
MTHF									
Energy content in hydrogen, €/ton raw material	19.8	19.5	19.6	20.7	20.4	27.3	23.7	22.3	20.6
By-product heat, €/ton raw material	23.8	22.7	21.6	21.3	20.6	22.6	19.8	11.9	12.6
Production costs, €/MWh product	19.9	21.0	21.5	21.0	19.8	19.2	20.4	22.3	30.8
Ethylene cost from ethanol + biogas									
By-product heat, €/ton raw material	38.4	39.0	42.7	40.6	41.0	36.4	32.3	32.5	32.6
Biogas, €/ton raw material	7.9	7.9	27.1	25.5	41.5	27.0	10.6	42.5	42.5
Operating by-products, €/ton raw material	39.5	38.9	16.0	19.7	3.3	22.4	42.9	10.8	10.8
Production cost, €/ton product	203.6	210.8	108.1	124.4	23.2	119.2	210.4	76.1	74.1

Table 3

Additional costs for normal, minimum and maximum cases

	Raw material, %	Electricity consumption, €/ton material	Raw material cost, %	Heat consumption, % raw material	Heat consumption per dry ton of material	Raw material cost, %	Enzymes costs, €/kg biomass	€/ton	Investment cost at LHV 300 MW feed	€/ton	Raw material cost, %	Min. production costs, €/ton	Raw material cost, %	Total prod. costs	Total, €/MWh
Min.	2	4.29	5.0	10	6.8	7.9	0.25	2.5	150	50.0	58.3	35.00	41.1	98.5	18.4
Norm.	5	10.7	13.0	20	14.0	16.0	0.5	5	350	117	136	70.00	82.1	215.9	40.3
Max.	15	32.2	38	30	20.0	24	2	20	550	183	214	100.0	117.0	355.8	66.3

Table 4

The influence of deviation of ideal yield and ideal energy yield on production costs

Total production cost per dry ton of biomass, €/MWh		20	20	20	20	30	30	30	30	40	40	40	40	50
Selectivity		1	0.9	0.8	0.7	1	0.9	0.8	0.7	1	0.9	0.8	0.7	1
		Total production cost of product, €/MWh												
Ideal LHV % of raw material	85	23.5	26.1	29.3	33.4	35.3	39.2	44.0	50.3	47.1	52.3	58.8	67.1	58.8
Ideal LHV % of raw	80	25.0	27.7	31.1	35.6	37.5	41.6	46.8	53.5	50.0	55.5	62.4	71.4	62.5

material														
Ideal LHV % of raw material	75	26.7	29.6	33.2	37.9	40.0	44.4	49.9	57.0	53.3	59.2	66.6	76.1	66.7
Ideal LHV % of raw material	70	28.6	31.7	35.6	40.7	42.9	47.6	53.5	61.1	57.1	63.5	71.4	81.6	71.4
Ideal LHV % of raw material	65	30.8	34.1	38.4	43.8	46.2	51.3	57.6	65.8	61.5	68.4	76.9	87.8	76.9
Ideal LHV % of raw material	60	33.3	37.0	41.6	47.5	50.0	55.5	62.4	71.4	66.7	74.1	83.3	95.2	83.3
Ideal LHV % of raw material	55	36.4	40.4	45.4	51.8	54.5	60.6	68.1	77.9	72.7	80.8	90.9	104.0	90.9
Ideal LHV % of raw material	50	40.0	44.4	49.9	57.0	60.0	66.6	75.0	85.6	80.0	88.9	100.0	114.0	100.0
Ideal LHV % of raw material	45	44.4	49.4	55.5	63.4	66.7	74.1	83.3	95.2	88.9	98.8	111.0	127.0	111.0
Ideal LHV % of raw material	40	50.0	55.5	62.4	71.4	75.0	83.3	93.7	107.0	100.0	111.0	125.0	143.0	125.0
Ideal LHV % of raw material	35	57.1	63.5	71.4	81.6	85.7	95.2	107.1	122.0	114.0	127.0	143.0	163.0	143.0
Ideal LHV % of raw material	30	66.7	74.1	83.3	95.2	100.0	111.0	125.0	148.0	133.0	148.0	167.0	190.0	167.0
Ideal LHV % of raw material	25	80.0	88.9	100.0	114.2	120.0	133.0.	150.0	171.0	160.0	177.8	200.0	228.5	200.0

For chemicals with low energy and high oxygen contents, such as acetic acid, the production cost per energy unit is lower than for fuel components – *e.g.* ethanol, because they are obtained in higher yield from the biomass. When the market prices of chemicals are considerably higher per energy unit compared to fuel components, a higher sales income is obtained. However, it should be kept in mind that their market size is much smaller than that of fuels. For hemicellulose, the sales income obtained might be higher when part of it is included in the fiber product, compared to biofuel production based on the energy content. However, lignin or spent cooking liquor utilization for biofuels increases the sales income, compared to energy production. Lignin utilization is particularly advantageous when the capacity of an external production unit can be increased, thus generating extra sales income with an existing production plant. In addition, lignin could be collected from several distributed production plants to the central lignin-based biorefinery, where it would be upgraded into biofuels and chemicals by a high yield method, such as gasification. The transport of lignin is more advantageous than that of other biomass, since its energy density is higher.

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ABBREVIATIONS

$C_{p,\ min}$ = minimum production cost for a production route of a main product (€/MWh or €/ton)

$C_{biomass}$ = cost of biomass per energy unit (€/MWh)

$C_{bioproduct}$ = revenue from by-products (€/ton of dry biomass)

η = yield of product in the ideal case (LHV% of raw material or ton per dry ton of biomass)

C_{ext} = cost benefit for an external process per ton of dry biomass (€/MWh)

$C_{heat,co}$ = heat consumption cost in the process (€/ton dry biomass)

C_{el} = electricity consumption cost in the process (€/ton dry biomass)

C_{chem} = cost of chemicals (€/ton dry biomass)

$C_{enzymes}$ = cost of enzymes (€/ton dry biomass)

C_{add} = additional cost, such as water treatment, logistics cost, etc. (€/ton dry biomass)

$C_{capital,\ ref}$ = capital cost for a reference plant with a known capacity (MW dry biomass feed on LHV basis)

F_{plant} = calculated capacity of the plant (MW dry biomass feed on LHV basis)

F_{ref} = reference plant capacity (MW dry biomass feed on LHV basis)

O_{annual} = annual hours of operation (h/a)

a_f = annuity factor

C_{fixed} = additional fixed cost, such as labour, maintenance etc., per year (€)

$M_{biomass}$ = calculated capacity of the plant (MW of dry biomass on LHV basis)

$Q_{biomass}$ = lower heating value for per ton of dry biomass (MW)

LHV = lower heating value (MWh/ton)

HHV = higher heating value (MWh/ton)

Z_{total} = selectivity of the total reaction sequence

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