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DEVELOPMENTS IN BIOENERGY PRODUCTION ACROSS THE WORLD - ELECTRICITY, HEAT AND SECOND GENERATION BIOFUELS

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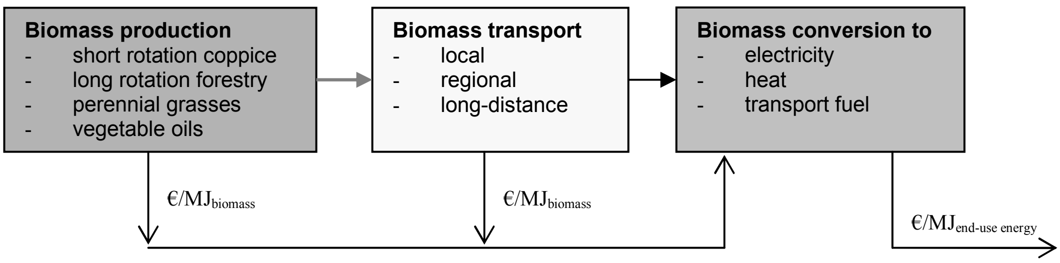
Introduction

1. This report contains explanations to a dataset on global bioenergy production that has been commissioned by the OECD, Directorate for Trade and Agriculture. The dataset has been developed to support a model-based analysis on the assessment of support policies to bioenergy from agriculture including biofuels, bioelectricity and bioheat. This report contains data on the production of biomass from agricultural land, transportation of biomass and its use for electricity, heat, 2nd generation biofuels and biodiesel from tropical vegetable oils. It complements the report of Smeets *et al*., 2005 on first generation biofuels.

2. The bioenergy chains studied consist of three parts, i.e. biomass production, transportation and energy conversion, see Figure 1. General parameters that characterize the costs of these parts of the chain are presented in the report, as well as formula's to calculate overall bioenergy costs from this data. For each part of the bioenergy chain, a number of representative options is included and two different level of technological development—current state-of-the-art and future developments in the next decade—are presented.

3. Data presented in this report are data that present the discussed options in a 'generic' way i.e. that describes the options generally. While ranges of data characterizing the different parts of the bioenergy chain can be large, the dataset, thus, presents a simplification by selecting average data. In order to select this dataset, we relied on major review publications that summarize various studies in the field of bioenergy. Ranges of values and the selection of data is discussed in the appendix.

Figure 1: Major parts of the bioenergy chains described in this report



Biomass production

4. In this section, the cost of biomass production systems is described. These costs are determined by the following parameter; see formula (1):

- crop yields
- capital costs of management in relation to yield level
- labour costs in relation to yield level
- land price component
- heating value, i.e. lower and higher heating value

$$C_{prod} = \frac{(MC + LC + \frac{LR}{yld})}{HV} \qquad (1)$$

C_{prod}: production costs of biomass [€/$MJ_{biomass}$]
MC: capital costs of management for biomass production [€/$MJ_{biomass}$]
lh: labour hours for biomass production [h/$MJ_{biomass}$]
LC: labour costs per amount of oven-dry (od) tonne of biomass produced [€/Mg_{od}]
LR: land rent [€/(ha*yr)]
yld: biomass yields [Mg_{od}/(ha*yr)]
HV: lower (LHV) and higher heating value of biomass in (HHV)[MJ_{LHV} or MJ_{HHV} per Mg_{od}]

5. Crop yields depend strongly on local conditions such as climate and soil. Moreover, crop yields are also influenced by the management system, e.g. the amount of fertilization, weeding and irrigation. Here, we give average yields for two different categories of land quality, i.e. low and high quality, i.e. and for two different categories of climate*, i.e.* temperate and tropical, even though ranges within these categories can still be large. It should be noted that in general yields between tropical and temperate regions do not vary considerably, while variations between different locations within the tropical or temperate region can be considerable, compare e.g. IIASA (2000).

6. Capital costs of management comprise costs for all inputs used into the production system, i.e. machinery, fuels, fertilizers, seeds, etc. These costs also comprise possible pre-treatment before the first transportation step of biomass. This pre-treatment consists of chipping in the case of ligno-cellulosic biomass and of milling and oil extraction in the case of oil seeds. Both capital costs of management and labour costs depend partly on amount of biomass harvested as a larger input, e.g. of fertilizer, does increase yields. On the other hand, management costs also depend on the area under cultivation as for example machinery hours often depend directly on the area managed. Here, we simplify this relation by assuming that management and labor costs depend directly on the amount of biomass harvested at a specific category of land (quality and climate). However, for future costs we assume that these decrease at a rate similar to the relative increase in yield. These relationships are based on the modeled costs for miscanthus in (Smeets *et al.,* draft).

7. For temperate regions, average land rents in the EU-25 are used as basis for estimates. These land rents range from about EUR 10 to EUR 420/ha for cropland and EUR 10 to EUR 360/ha for grassland, while average rents are about EUR 180/ha and EUR 144/ha. It is assumed that rental costs of extensive grassland and low quality agricultural land are 30% lower than average rents, while good quality agricultural land has 30% higher rents.

8. Land rents for tropical agricultural lands have estimated by average rents for abandoned agricultural land in 2020 in Asia, Africa and Latin America as presented in (Hoogwijk, 2004). Land rents for palm oil production are higher than for jatropha production as it is assumed that palm oil is produced in South-East Asia and jatropha in Africa and South Asia.

9. In general, it should be noted that no consistent datasets for global land rental prices are available and that the dataset of (Hoogwijk, 2004) is based on natural capital estimates that have been corrected for the quality of abandoned agricultural land. As a consequence, the land rents used in this report are rough regional estimates and are highly uncertain.

10. Finally, lower and higher heating values are used to determine the costs per energy content of the biomass. These values are taken from average estimates from a biomass composition database 'Phyllis'. While, heating values of single samples of a biomass category can vary about ± 2 GJ/Mg_{od}, overall estimates are rather certain.

11. In this section, biomass production systems for the production of 2nd generation biofuels are regarded. These are production systems for lignocellulosic plants, i.e. the production of wood and herbaceous crops. Moreover, also tropical vegetable oils, i.e. palm oil and jatropha oil, that can be produced on degraded land and that are suitable for the production of biodiesel are included.

Lignocellulosic crops

Short rotation forestry on agricultural good quality land

12. Short rotation forestry production systems grow trees in very short rotation of about 3-6 years. In temperate regions, willows and poplar are common species for short rotation forestry with rotation cycles of 3-4 years, while in the tropics mainly eucalyptus is used in short rotation forestry systems of about 4-6 years.

13. Short rotation forestry (SRF) systems are often established at former agricultural land with a good quality. For lower quality land, often more extensive systems like grassland and longer rotation forestry are used. The average yield of SRF in Europe on suitable land[1] is about 10.3 Mg_{odt}/ha/yr, (Sims, 2006), which is a little bit higher than current global average yields of 8.4 Mg_{odt}/ha/yr and lower than the average yields on very suitable lands of 14 Mg_{odt}/ha/yr. (Smeets, 2007). For the tropical regions, we assume global average yields on suitable land assuming a management factor of 0.8[2], according to data presented in (Smeets, 2006).

14. Future estimates for yields vary widely, e.g. from 16-39 Mg_{odt}/ha/yr in 2050 in tropical regions and from 19-36 Mg_{odt}/ha/yr in temperate regions which is equivalent to a management factor of 1.5 (Smeets, 2007). For tropical and temperate regions we assume for the future yields in 2020 an increase of current yields up to a management factor of 1.2.

15. The costs of short rotation forestry are estimated according to case studies for Nicaragua (eucalyptus) and the Netherland (willow) as presented by Hoogwijk (2004). It assumed that harvesting of short rotation wood includes chipping and that wood chips with a moisture content of about 50% enter the transportation chain.

1 Land is divided by the AEZ methodology (IIASA, 2000) into 5 distinctive categories with decreasing quality: very suitable, suitable, moderately suitable, marginally suitable and non-suitable.

2 Yields are about 80% of management constraint free yields

Long rotation forestry on agricultural low quality land

16. Forestry with longer rotations than about 20 years is typically established on lower quality lands that are economically not suitable for agricultural production. In tropical regions degraded and marginal land can be used for production of vegetable oils from trees and bushes. Therefore, we only consider long rotation forestry in temperate regions in this section. Typical species for forestry in these regions are spruce, fir and pine with rotation times of 40 to 120 years depending on soil and climate. It is assumed that the whole amount of wood from afforestation is used for bioenergy.

17. Yields of forestry are estimated by average net annual increment (NAI) of forests as these are typically established on low quality land. While it is possible to increase future yields of long rotation forestry by management practices, e.g. by fertilization, this practice is typically not applied. Therefore, we assume no increase in future yields of forestry. Costs of forestry and a split between labour and capital costs are taken from Swedish statistics (Skogstyrelssen, 2007). Wood is assumed to be chipped and to be transported with a moisture content of about 35%.

Perennial grasses on agricultural good quality land

18. Perennial grasses such as miscanthus, switchgrass and reed canary grass are a fast growing energy crop that can be produced on agricultural land. After establishment, these grasses are harvested every year. As for short rotation forestry, perennial grasses are often produced on relative good qualities of land as production is more intensive and inputs are higher than for long rotation forestry.

19. Average yields of perennial grasses in Europe are about 13 Mg_{od} (Sims, 2006) while yields range from about 9-22 Mg_{od}. For the future, we assumed a yield increase of 20% as in the case of short rotation forestry. Capital and labour costs are comparable to average costs of miscanthus production in Europe, as modeled by (Smeets et. al., draft).[3] Costs in the US are slightly lower. (Hallam, 2001). Chopping of the grass is included in the harvesting procedure and chopped grasses are assumed.

Perennial grasses on extensively managed grasslands

20. Land that is of low quality for the production of agricultural land is often used as grassland or pastures. These grasslands are typically extensively managed and have relative low biomass yields.

21. Yields of extensive grassland on low quality agricultural land are about the net primary production, i.e. production without management. (Scurlock et al., 2002) Average values for humid temperate regions are 3.5 Mg_{od} and for humid savannah about 4 Mg_{od}, which is about the global average estimated by (Wolf et al., 2003). No cost estimates of harvesting biomass from extensively managed grasslands could be identified. Therefore, the costs of extensive grassland management are based on modeled management costs for harvesting of perennial grasses in temperate regions. Thus, it is assumed that besides harvest no management takes place.

[3] Even though establishment procedures and yields differ between switchgrass, miscanthus and reed canary grass; (Smeets, et al., draft. Hallam, 2001 and also de Wit and Faaij, in preparation) come to comparable ranges of production costs. However, depending on actual yields and costs of production such as labour capital, etc. costs between different perennial grasses can vary.

Oilseed crops from tropical areas

Palm oil on tropical land

22. Oil palms are cultivated in tropical regions and are cultivated on different types of land, e.g. on land that has been converted from forests to oil palm plantation (implying deforestation) and on degraded/marginal lands. Palm oil plantations have quite high biomass yields. Currently main areas of production are Malaysia and Indonesia. Oil palms produce fruits from which palm oil can be extracted. Typically fresh fruit bunches are harvested at the palm tree plantation. Trees can be harvested every 14 to 21 days and are transported to a local mill in which the crude palm oil (CPO) is extracted. Production costs and yields given in this overview are given per Mg CPO and thus include operations at the plantation, transport to the mill and extraction of oil. Several by-products are generated during mill of the fruit, among those the only by-product that is used externally is palm kernels, which can be pressed for extracting palm kernel oil and also obtaining press cake as a by-product, which is suitable as animal feed. Revenues from palm kernels are included in the capital production costs.

23. Average oil yield within Malaysia, Indonesia and Thailand is 3.2 Mg oil per hectare per year but can range between 1.7 to 6.6 Mg oil per hectare per year, depending on the fruit production yield (10 to 30 tonne fresh fruit bunches per hectare per year) and the oil extraction rate (17 to 22%) (Chavalparit, 2006) and a revenue of EUR 195 per Mg kernels (MPOB, 2006) is assumed, reducing the capital costs by EUR 31 per Mg CPO. For the future, an oil yield of 5.5 is assumed - referring to a fruit yield of 25 Mg fresh fruit bunches per hectare per year and an oil extraction rate of 22% from fresh fruit branches (of which about 60-65% consist of fruits).

24. There are multiple by-products of palm oil extraction but most of these are consumed within in the palm oil production system. Empty fruit bunches are returned to the plantation as fertilizer, which palm kernel shells and fibre are used for meeting steam and electricity requirements of the mill. The only by-product used outside the system is the palm kernels. Kernels are pressed for extracting palm kernel oil, with a by-product, palm kernel expeller, which can be used as animal feed. Kernels are produced at a rate of 0.23 kg per kg CPO (Chavalparit, 2006). The cost of CPO production is estimated based on Ahmad et al. (2004).

Jatropha oil on tropical land

25. Jatropha shrubs that produce oil containing crops can grow on agricultural land with very low quality. In recent years, the production of jatropha has become more important and currently plantations are established on a larger scale in, for example, Africa and India. As for palm oil, extraction of oil is included in the data presented in this section. Therefore, also the revenues from the by-product of pressing the seeds for oil extraction are included.

26. Average oil yield on degraded/marginal land is 2 Mg oil per hectare per year. This yield can range between 1 to 4 Mg oil per hectare per year depending on the quality of the land. The oil yield is based on the seed yield (4 to even 8 tonne seeds per hectare per year) and the oil extraction rate (25 to 35%) (Foidl *et al*., 1996; Del Greco and Rademakers, undated). For the future, an oil yield of 2.8 is assumed - referring to a seed yield of 8 tonne per hectare per year and an oil extraction rate of 22%. The extraction of oil from the jatropha seeds produces seedcake as a by-product, which can be used as organic fertilizer; 2.1 kg press cake are produced per kilogram crude jatropha oil (Biswas et al., undated). Del Greco and Rademakers (undated) estimate that the 1 tonne of seedcake is equivalent to about 200 kg of mineral fertilizer (NPK 12:24:12), the price they use is 35 Euro per Mg seedcake (Openshaw, 2000), reducing the capital costs by 55 Euro per Mg crude jatropha oil. Production costs of jatropha oil are based on Openshaw (2000).

Figure 2: Current and future costs of biomass production according to the data presented in Table 1. (Note that for oil crops, costs are given per GJ vegetable oil which has in general a higher value than a GJ of lignocellulosic plant material.)

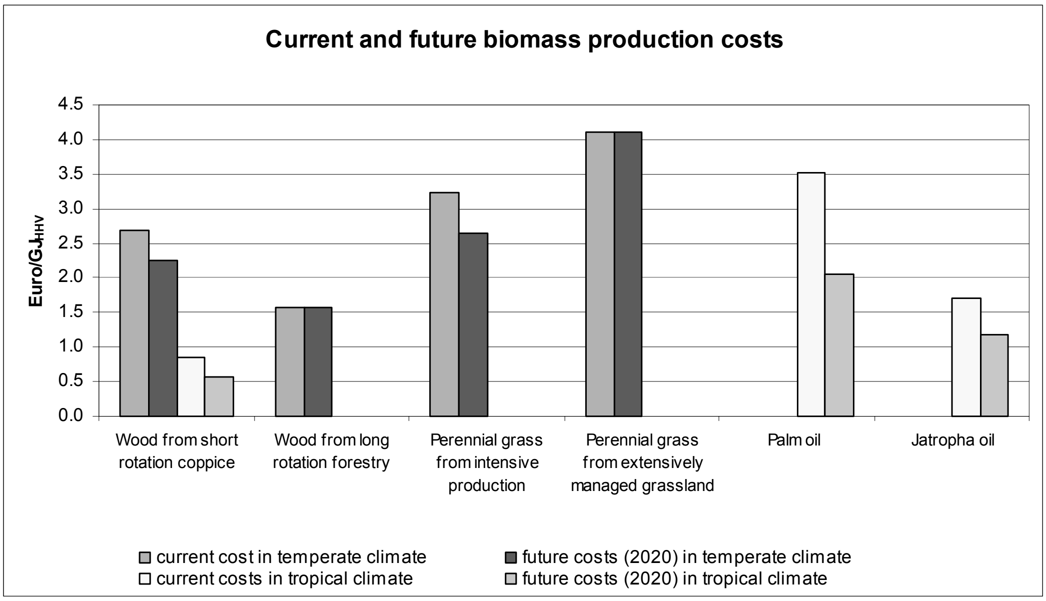


Table 1: Input data for the calculation of biomass production costs (data based on Wolf et al. 2003, Smeets and Faaij (forthcoming) Sims et al., 2006, Hoogwijk, 2004, Hallam et al., 2001, Skogstyrelsen, 2007, Smeets et al., 2007, van den Broek, 2000, Scurlock et al., 2002)

Crop and climate zone	Time	type of land	Yields	Lower heating value	Higher heating value	Capital costs of management	Labour costs	Land rent
			Mg_{od}/ha/yr	GJ_{LHV}/Mg	GJ_{HHV}/Mg	€/Mg_{od}	€/Mg_{od}	€/ha/yr
Short rotation coppice								
temperate	Now	agriculture good quality	10	18.5	19.8	25	4	240
temperate	2020	agriculture good quality	12	18.5	19.8	21	3.5	240
tropical	Now	agriculture good quality	16	18.3	19.6	6	2.5	130
tropical	2020	agriculture good quality	24	18.3	19.6	4	1.7	130
Long rotation forestry								
temperate	Now	agriculture low quality	5.2	18.5	19.8	1.8	5.4	125
temperate	2020	agriculture low quality	5.2	18.5	19.8	1.8	5.4	125
Intensive perennial								
temperate	Now	agriculture good quality	13	18.3	19.6	33	12	240
temperate	2020	agriculture good quality	16	18.3	19.6	27	10	240
Extensive grassland								
temperate	2007	extensive grassland	3.5	18.3	19.6	37	15	100
temperate	2020	extensive grassland	3.5	18.3	19.6	37	15	100
Palm oil production								
tropical	2007	tropical land	3.2	35.2	37.6	46 (€/Mg_{oil})	55 (€/Mg_{oil})	100
tropical	2020	tropical land	5.5	35.2	37.6	27 (€/Mg_{oil})	32 (€/Mg_{oil})	100
Jatropha oil production								
tropical	2007	tropical land	2	36	38	37 (€/Mg_{oil})	13 (€/Mg_{oil})	30
tropical	2020	tropical land	2.8	36	38	26 (€/Mg_{oil})	8 (€/Mg_{oil})	30

Logistics

27. From the place of production, biomass is transported to the conversion installation where it is converted to transport fuel, heat or electricity. This transportation consists of several transportation steps, e.g. local transport per truck and internal long-distance transport per ship. Note that in practice also storage and further handling along the supply chain occur, but that these steps are not included in this report. Included in the logistics chain in this report are the loading/unloading of transportation means and in some chains pre-treatment steps such as pelletizing takes place. Harvesting is accounted for in the biomass production section. According to formula 2, these simplified costs of transport are determined from:

- the specific costs of transport per Mg and km
- the average distance
- the moisture content of the material transported
-

$$C_{tr} = \frac{spt + \sum_{i=1}^{n} d_i \cdot stc_i}{HV} \qquad (2)$$

C_{tr}: cost of transport [€/MJ_{bio}]
n: number of transportation steps [-]
spt: specific costs of pelletising(if applicable) [€/Mg_{od}]
stc_i: specific transport costs of transport mode used in step i [€/(Mg_{od}*km)]

with:
$stc_i = (ec_i + mc_i) + lc_i/d_i$
ec_i: specific energy costs of transport mode used in step i [€/(Mg_{od}*km)]
mc_i: management costs of transport mode used in step i [€/(Mg_{od}*km)]
d_i: distance in transportation step i [km]
lc_i: specific loading/unloading costs of transport mode used in step i [€/(Mg_{od})]

28. Costs of transport depend on both on fixed costs and to variable costs related to the distance of the good to be produced. Costs are therefore not linearly related to average distance in km as for example capital costs for means of transport are included in specific costs. Other variable costs that apply to transport chains are the costs of fuel and the costs of loading and unloading. Therefore, these specific transport costs have been split into the costs for loading/unloading, the costs for energy during transportation and other specific management costs of transport. The specific management costs given in Table 2 still include variable and fixed and as a consequence apply at the distances given, but change at different distances.

29. Data on the transportation chains such as average distances and specific costs of transportation are taken from a biomass logistic tool that has been developed at the Copernicus Institute, Utrecht University and of which results are presented in Hamelinck *et al.,* 2005. Costs depend on the type of transport (e.g. full-load capacity of ships), on the density of the biomass transported and on cost factors such as labour, energy, etc. As a consequence resulting biomass costs vary.

30. Here, we assume 3 simplified logistic chains for the transportation of solid biomass, i.e. perennial grasses and wood and 1 chain for transportation of liquid biomass. It is assumed that biomass transport chains are straightforward, i.e. assuming few handling steps. Note that in practice, biomass logistic chains can be more sophisticated:

1. Local transport of solid biomass

31. For this chain, it is assumed that biomass converted into energy near to its place of production. This is possible for small-scale to medium scale uses. It is assumed that biomass as harvested including chipping/chopping is transported about 100 km to the conversion installation. This is about the maximum distance for which truck transport is economically favourable to inland ship or train transport. For European situation, installations with up to 2000 MW input are possible with this distance.

2. Regional transport of solid biomass

32. Regional transport considers the transport within a continent to a more central biomass conversion installation. First, the biomass is transported locally, i.e. about 50 km by truck and then pelletised. For longer transports by ship or train, densification of biomass is economically favourable. Here we assume the transport of pellets. Briquetting is also a possible option for densifiying but does not differ in terms of economics too much from pelletising. The transportation distance of 800 km that is used as an average distance for regional transport, corresponds for example to distances between the Netherlands and Poland.

3. International long-distance transport of solid biomass

33. International long-distance transport assumes intercontinental biomass transport with overseas ships. This describes a situation with long-distance international bioenergy trade, e.g. from developing to industrialized countries. Also for overseas transport, densification of solid biomass is economically advantageous and, therefore, biomass is first transported locally and pelletised as in the regional transport chain. Afterwards, pellets are transported overseas with an average distance of 11 000 km. This distance of 11 000 km is about the distance between Latin America and Europe. For this transport a large-scale ship, i.e. Panamax is assumed. After ship transport, a local transport of about 100 km to the final conversion installation takes place as it is also assumed that the conversion installation is not situated directly in the harbour as this will not be the case for all installations. However, large-scale biomass conversion installations that rely on imported biomass could be located at the harbour and in that case the last transportation step would not be needed.

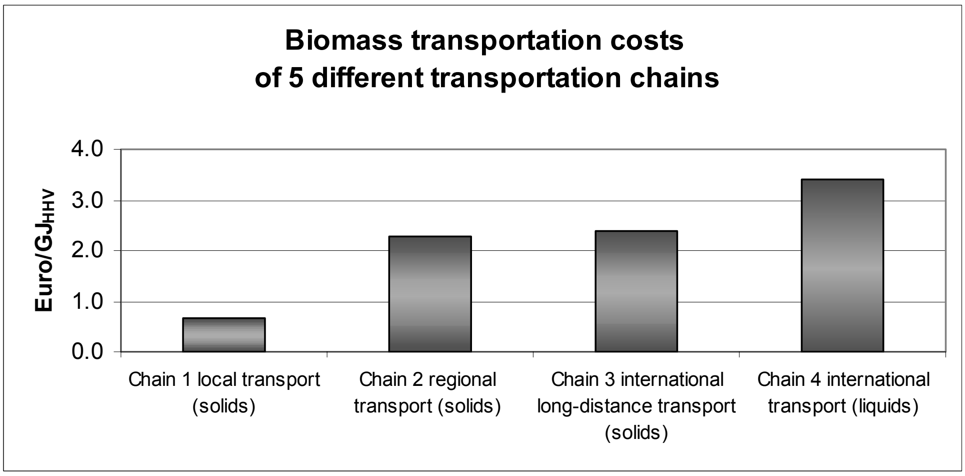
4. International long-distance transport of liquid biomass

34. In the case of palm oil production, it is assumed that local production of biodiesel takes place close to the palm oil mill and that no additional transport is needed. Moreover, it is assumed that fuel from tropical vegetable oils is either used locally or at long-distances in industrialized countries. Therefore, only long-distance transportation of liquids, i.e. either CPO or biodiesel, is assumed. As CPO or biodiesel are already concentrated at the palm oil mill, the chain start with truck transport to the harbour and continues with intercontinental ocean ship transport. As in the case of solid long-distance transport, a transportation step to the conversion installation is included at the end of the chain. Chain 4 is similar in distances to chain 3 transporting solid biomass. However, values for the transport of liquids in trucks and ships are used.

Table 2: Input data for costs of biomass transport chains

Step	type of transport	distance [km]	spec. management costs [€/Mg_{od}/km]	energy costs [€/Mg_{od}/km]	loading/unloading [€/Mg_{od}]	specific costs pelletising [€/Mg_{od}]
Chain 1 local transport (solids)						
1	truck	100	0.095	0.008	2.98	N/A
Chain 2 regional transport (solids)						
1	truck	50	0.151	0.0075	2.98	N/A
2	pelletising	N/A	N/A	N/A	N/A	22.6
3	train	800	0.018	0.006	0.38	N/A
Chain 3 international long-distance transport (solids)						
1	truck	50	0.151	0.008	2.98	N/A
2	pelletising	N/A	N/A	N/A	N/A	22.6
3	truck	100	0.034	0.004	0.84	N/A
4	ocean ship	11000	0.001	0.0002	1.84	N/A
5	truck	50	0.046	0.004	0.84	N/A
Chain 4 international long-distance transport (liquids)						
1	truck	100	0.150	0.015	0.4	N/A
2	ocean ship	11000	0.009	0.0019	1.6	N/A
3	truck	50	0.179	0.015	0.4	N/A

Figure 3: Biomass transport cost for the 4 transportation chains assuming a higher heating value for solid and liquid biomass of 19.6 and 36 GJ/Mg_{od}



Conversion technologies

35. In this report, three categories of the conversion of biomass to energy are included:

- Production of electricity including combined heat and power (CHP) production
- Production of heat
- Production of so-called '2nd generation biofuels' and production of biodiesel from vegetable oils

36. The costs of energy conversion are calculated from the yearly capital and operational costs of the installation, the yearly fuel costs, the efficiency of conversion, the operation hours in a year and possible revenues from by-products; see formula (1). The term 'energy' in this formula refers to the f energy produced from biomass, i.e. heat, electricity or transport fuels. [4]

$$C_e = \frac{INV \cdot (af + OM\ )}{lf \cdot 3600} + \frac{C_{prod} + C_{tr}}{eff} + M_{by-p} \cdot P_{by-p} \qquad (3)$$

C_e : costs of energy production (electricity, heat, transport fuel) [€/MJ]
INV: specific investment costs per output capacity (electricity, heat, fuel) [€/MW]
s: scale of installation in output capacity (electricity, heat, fuel) [MW]
af: annuity factor with af= $r/(1-1/(1+r)^t)$ [1/yr] and r: interest rate [-], t: lifetime [yr]
OM: yearly operation and maintenance costs as ratio of total investment [1/yr]
C_{tr}: biomass transport costs [€/MJ_{bio}]
lf: loadfactor of conversion installation [hours/year]
eff: efficiency of conversion [$MJ_{energy}/MJ_{biomass}$]
B: benefit from by-products [€/MJ_{energy}]
M_{by-p}: Amount of by-product [kg or MJ_{th} or MJe per MJ_{energy}]
P_{by-p}: Amount of by-product [€ per kg or MJ_{th}]

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4 Conversion efficiency of heat and electricity production are given per MJ_{LHV} of biomass, while conversion efficiencies of transport fuel production are expresses per MJ_{HHV} of biomass.

37. As a basis assumption, we used a lifetime of 20 years and an interest rate of 6% in the calculation of energy costs. However, these variables can easily be adapted in the spreadsheet.

38. In the case of CHP production, electricity is considered the main energy carrier produced, while heat is considered a by-product. The basis assumption here is a heat price of EUR 0.011/MJ[5] and a heat load of 2500 h/yr. These assumptions are easily adaptable in the spreadsheet, too. During the production of transportation fuels, i.e. of ethanol, Fischer-Tropsch diesel and methanol, electricity is co-produced. This electricity is credited with a basis price of EUR 0.03/kWh that can be varied. Other by-products occur during the production of biodiesel from vegetable oils; see section 2.3.

Conversion technologies for electricity production

Co-firing in coal power plant

39. Biomass is often directly co-fired—i.e. without prior gasification of biomass—in existing coal fired power plants. During co-firing, the biomass is mixed with coal and then combusted together in a boiler. Typical co-firing ratios are up to 10%, while in newer multi-fuel power plants higher shares of about 40% are possible which is taken into account for future capacities of coal power plants.

40. Efficiencies of coal power plants range broadly from about from 30-44%, while current medium to large scale plants range between 35-39 % (Sims et al., 2006). Specific investment costs range from about EUR 150-250/kW$_e$ and average costs as stated by Faaij, 2006a are assumed. Operation and maintenance (O&M) costs are derived from Resch et al, 2007, while load are assumed to be average hours of a coal fired power plant. For future co-firing technologies, favorable extremes of efficiency as coal-power plants are assumed to be more advanced.

Grate firing

41. Grate firing combusts biomass or other fuels directly, while the fuel is transporter in the boiler on a ‘moving grate’. It is a well established technology for which no major developments are expected, especially for waste incineration. Scales of current biomass stand-alone power plants using grate firing are comparatively small 20-50 MW$_e$ and electrical efficiencies are relatively low.

42. Electrical efficiencies range from 25% to 30% for modern biomass installations. Specific investment costs for biomass combustion installation including grate firing and fluidized bed combustion, range from EUR 2 500 to EUR 1 600/kW$_{e..}$ (Faaij, 2006a), with costs in the range around EUR 1900/kWh, (Dornburg and Faaij 2001), Dornburg *et al.* 2006). No future developments are assumed for grate firing.

Fluidized bed combustion (biomass stand-alone power production)

43. In fluidized beds, combustion takes place while the fuel circulates with the air within the boiler. The combustion of biomass in fluidized bed boilers is a more recent development and allows for higher electrical efficiencies of about 30 to 40%. Average scales are about 100 MW$_e$

5 Future prices in the Netherlands are predicted to be about EUR 0.011/MJ (Dornburg and Faaij, 2006), while e.g. current prices of district heating in Germany are between EUR 0.013-0.018/MJ (Broekeland, 2006).

with a tendency to larger plants as for example the latest power plant in Finland with this technology is about 500 MW_e.

44. Typically specific investment costs are estimated from (Dornburg et al. 2006) Dornburg et al. 2006 and it is estimated that in the future lower ranges of the costs stated in (Faaij, 2006a) will be reached. Electrical efficiencies of combustion reach from 30-40% and also here future developments are assumed.

Combined heat and power production from biomass combustion

45. Combined heat and power (CHP) production can use various concepts of biomass combustion and gasification. CHP production using steam turbines and biomass combustion in grate firings and fluidized bed boilers is a common technology in many parts of Europe, e.g. in Scandinavia. CHP is produced from grate firing plants as well as from CFB/BFB combustion at small to medium scales with the trend being that new plants have increasing electric and overall efficiencies, the latter of up to 100%. Also scales tend to increase. Here, we regard medium scales of 5 to 35 MW_e that are suited for district heating and electricity production purposes.

46. Specific investment costs of CHP production from biomass combustion are comparable to investment costs from biomass combustion for power only. We assumed investment costs as for grate firing as this technology is often used in smaller –scale CHP applications. Moreover, as efficiencies tend to increase with recent developments and scales, overall efficiencies are estimated to increase from 80 to 100% between small-scale current applications and medium-scale future applications.

BIG/CC stand alone power

47. In biomass integrated gasification with combined cycle (BIG/CC) plants, biomass is first gasified, i.e. biomass is thermo-chemically converted to synthesis gas using less oxygen than would be needed for combustion. The resulting synthesis gas is used in combined cycles, i.e. electricity production from gas turbines of which rest heat is used in steam turbines. BIG/CC technology is currently still in demonstration phase with small plants of currently about 30-100 MW_e, while in the longer term larger scales will be possible. Developments are envisioned. with efficiencies of 40% are possible. Therefore, we consider BIG/CC only for the longer term in 2020 after further developments leading to electric efficiencies of about 47%. (Efficiencies of this technology are between 40-50% (Faaij, 2006a), while (Dornburg et al., 2001) give future ranges of about 45-47%).

Co-gasification and use in a natural gas power plant

48. In this concept biomass is gasified and the resulting synthesis gas is used in a natural gas power plant, where it is used together with natural gas in gas turbines. In current installation, biomass is gasified, but the synthesis gas from gasification is then used for combustion as the use in gas turbines has relatively high requirements on the quality of the synthesis gas. However, as synthesis gas can currently be used in gas turbines and has much higher electrical efficiencies — see BIG/CC technology—we consider this technology for the future in 2020.

49. For the scale of co-gasification, we assume that about 10% and that biomass is used in a large-scale natural gas power plant leading to efficiencies of about 49% (Rodrigues *et al.,* 2003). Cost data are derived from (Resch *et al.,* 2007) and load hours will depend on the use of the natural gas power plant. Here, we assumed a full-load of 6000 hours/year (Resch *et al*., 2007)

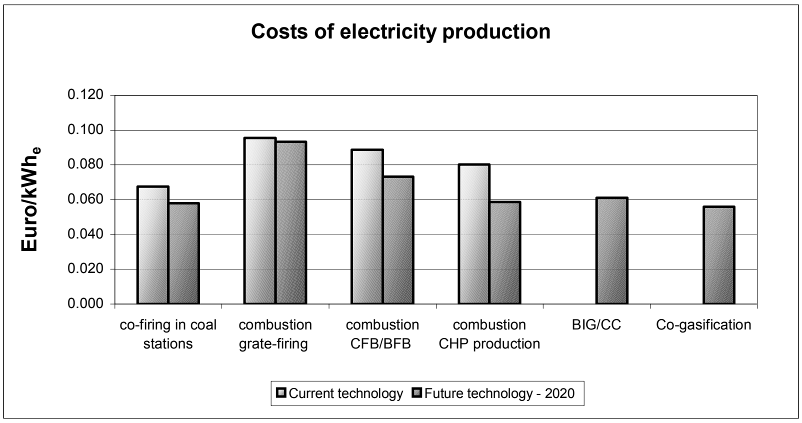
Table 3: Input data for conversion to electricity (based on data from Faaij, 2006a/b, Resch et al., 2006, Sims et al., 2006, Dornburg et al., 2006, Dornburg and Faaij, 2001, Rodrigues et al., 2003)

	Time	Capacity (MW_e)[a]	investment costs (€/kW_e)[b]	O&M costs (% of investm.)	load factor (h/yr)	net electric efficiency (MJ_e/MJ_{LHVo})	net heat efficiency (MJ_{th}/MJ_{LHV})
co-firing in coal stations	Now	10	250	38	6500	0.37	N/a
co-firing in coal stations	2020	40	250	38	6500	0.44	N/a
grate-firing boiler	Now	35	1900	4	7000	0.3	N/a
grate-firing boiler	2020	35	1900	4	7000	0.3	N/a
CFB/BFB	Now	65	2000	4	7000	0.35	N/a
CFB/BFB	2020	200	1600	4	7000	0.4	N/a
BIG/CC	2020	200	1500	6	7000	0.47	N/a
Co-gasification	2020	50	810	6	6000	0.49	N/a
CHP combustion	Now	5	2100	4	7000	0.25	0.55
CHP combustion	2020	35	1900	4	7000	0.35	0.65

[a] For the co-firing options, the capacity of electricity produced from biomass only is given.

[b] For the co-firing options, costs are additional costs of biomass co-firing, while the basic investments for the fossil fuel power plant are not taken into account.

Figure 4: Resulting electricity costs at fuel costs including transportation of 5 €/GJ_{LHV} with basis assumptions of heat prices of 0.011 €/MJ[6], heat load of 2500 h/yr, lifetime of 20 years and interest rate of 6%.



Conversion technologies for heat production

50. For heat production, load hours depend on the local heat demand, which vary strongly between countries and between types of uses. Here, we use average assumptions for small and medium-scale uses for Europe. (Resch *et al.,* 2007)

6 Future prices in the Netherlands are predicted to be about EUR 0.011/MJ (Dornburg and Faaij, 2006), while e.g. current prices of district heating in Germany are between EUR 0.013-0.018/MJ (Broekeland, 2006)

Traditional stoves (and fireplaces)

51. Traditional stoves and fireplaces have been used for many centuries for cooking and heating purposes. Capacities of traditional stoves and fireplaces are in the range of 5-50 kW_{th} and typical efficiencies are around 10% (Faaij 2006b), while ranges of capacities are very large from negative efficiencies due to heat losses via the chimney during the year to efficiencies of up to 20-30%. Investment costs are assumed to be in the lower range of data given for small-scale domestic combustion applications (Faaij, 2006b) and operational costs are assumed to be about the same as for other small scale domestic heating technologies.

Domestic heating

52. For domestic heating with biomass resources, usually boilers using wood chips or wood pellets are used. Capacities are typically small (about 5-50 $kW_{\mathbf{th}}$), while efficiencies can range from about 70-90% depending on the type of technologies. We regard applications with average size of about 30 kWth. Investment cost estimates of wood chip boilers are in the range of about 450-600 €/kW_{th} and we assume costs of about 500 €/kW_{th}. Efficiences are assumed to be high with average efficiencies of about 87% (Resch *et al.*, 2007) and increasing efficiencies of 90% for the future as are typical for condensing boilers (Sims, 2006).

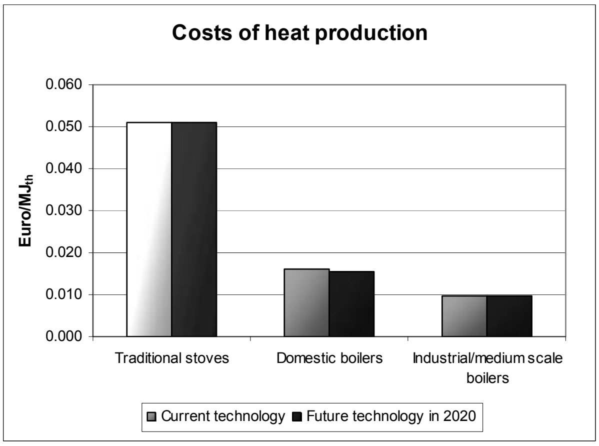
Industrial/medium scale boilers

53. Industrial or medium scale boiler have a capacity of about 1-5 MW_{th}. These are typically used for district heating, heating of larger public buildings and for process heat in small enterprises. Average data for this type of boiler are taken from (Resch *et al.*, 2007) that estimate efficiency ranges of about 85-87% for local heat plants, while investment costs range from EUR 430-475/$kW_{th.}$ Efficiencies are in the same range as for domestic boilers.

Table 4: Input data for conversion to heat (based on data from Faaij, 2006a/b, Resch et al., 2006, Sims et al., 2006, Gustavsson et al. 2006)

	Time	Capacity (MW_{th})[a]	Investment costs (€/kW_{th})[b]	O&M costs (% of investm.)	Load factor (h/yr)	Net heat efficiency (MJ_{th}/MJ_{LHV})
Traditional stoves	Now	0.005	100	3	1600	0.10
Traditional stoves	2020	0.005	100	3	1600	0.10
Domestic boilers	Now	0.03	500	3	1600	0.87
Domestic boilers	2020	0.03	500	3	1600	0.90
Industrial boilers	Now	2	450	4	4000	0.87
Industrial boilers	2020	2	450	4	4000	0.90

Figure 5: Resulting heat costs at fuel costs including transportation of 5 €/GJ_{LHV} with basis assumptions: lifetime of 20 years and interest rate of 6%.



Conversion technologies for the production of transportation fuels

54. For the production of 2nd generation transportation fuel, technological concepts vary in detail. For example, gasifiers can use air or oxygen, hydrolysis of lignocellulose can be done enzymatically or with liquid hot water treatment, etc. Costs and efficiency estimates of these technologies are often derived from process modeling and the results depend on the specific concept assumed. As a consequence, estimates of future production costs can vary widely, see e.g. Table A1.

55. Here, we use a dataset from (Faaij, 2006 a/b), that describe kind of 'generic' results derived from various studies on concepts. Only for the production of ethanol, we use data from (Hamelinck and Faaij, 2006), as data from (Faaij, 2006a/b) assume a technological breakthrough, while assume less radical but still considerable technological development. Typical scales of operations are derived from (Hamelinck and Faaij, 2006). All data for 2nd generation biofuels are based on higher heating values (HHV).

Ethanol from lignocellulose

56. To produce ethanol from lignocellulose, the feedstock has to be pretreated by hydrolysis to convert lignocellulose into lignin and fermentable sugars. Lignin is removed and converted to electricity, while the sugars are fermented to ethanol. The technology for fermentation is already well developed from the production of ethanol, from e.g. sugar cane. On the other hand, the technology for the hydrolysis step is still under development. Currently, acid pretreatment is used even though it is not very efficient and rather expensive. Enzymatic pretreatment is still under development, but might lead to lower costs after it has been proven commercially.

Methanol, Fischer-Tropsch and Hydrogen via gasification

57. Methanol, hydrogen and Fischer-Tropsh liquids are 2nd generation transport fuels that can be produced from biomass via gasification. The synthesis from gasification is cleaned and then fuels are produced via catalysis and/or separation. Technologies for production are still in the commercialization stage and major issues for further technological development are gas cleaning, scale-up of processes and process integration.

Biodiesel from palm oil

58. Crude palm oil is transesterified with methanol and a potassium hydroxide catalyst to produce methyl esters, i.e. biodiesel. The net fuel efficiency of biodiesel from palm oil, 1 MJ_{fuel}/MJ_{HHV}, is above one as the energy input from methanol, with which crude palm oil is reacted, is not accounted for.[7] This process covers all steps from crude palm oil to biodiesel production, crude palm oil production (the extraction of oil from the fruit) is included in the biomass production section above.

59. Investment costs of biodiesel production from palm oil are estimated based cost information from Choo *et al*. (2005), who describe a plant that produces 60 000 tonne biodiesel per year and investment costs are EUR 8.5 million. The future investment cost is estimated by applying a scale factor of 0.95 (scale factor for biodiesel from rapeseed, Smeets *et al*., 2005). Operation and maintenance costs and load factors are assumed to be similar to those of biodiesel production from rapeseed and taken from Smeets *et al*. (2005).

60. As a by-product of the biodiesel production, 0.1 tonne glycerine per tonne CPO input is generated (Smeets *et al.,* 2005 and Choo *et al.* 2005). Glycerine can be used for making cosmetics, medicine and foods, and improves the economics of biodiesel production. However, with an increased glycerine production at biodiesel plants, the market price of glycerine has already dropped and may drop to zero or become even negative (Smeets *et al*., 2005). The current glycerine price is based on Smeets *et al*. (2005) and amounts to 0.05 Euro per kilogramme. As mentioned above, glycerine prices have already declined and are expected to decrease further, maybe even reaching zero or a negative price. Therefore, the future glycerine price is assumed to be zero.

Biodiesel from Jathropha

61. Jatropha oil is converted to biodiesel by transesterification, the chemical reaction of jatropha oil with methanol. The output is methyl ester and glycerine as a by-product. As for biodiesel from crude palm oil, the net fuel efficiency of jatropha biodiesel is near to one because of the energy input by methanol. The value of glycerine and the expectation that prices may decrease with increased biodiesel production should be noted; see the section on biodiesel from palm oil.

62. Investment costs of biodiesel production from jatropha oil are estimated based on cost information from Biswas et al (undated), who suggest a range of EUR 260 to 350 per tonne biodiesel produced depending on the scale of production. The current investment cost is assumed be equal to the higher value. The future investment cost is estimated by applying a scale factor of 0.95 (scale factor for biodiesel from rapeseed, Smeets *et al.,* 2005). Operation and maintenance costs and load factors are assumed to be similar to those of biodiesel production from rapeseed and taken from Smeets et al. (2005). As a by-product of the biodiesel production, 0.11 tonne glycerine per tonne CPO input is generated (Smeets *et al.,* 2005 and Biswas *et al,* undated). The current glycerine price is based on Smeets *et al*. (2005) and amounts to EUR 0.05 per kilogramme. As mentioned above, glycerine prices have already declined and are expected to decrease further, maybe even reaching zero or a negative price. Therefore, the future glycerine price is assumed to be zero.

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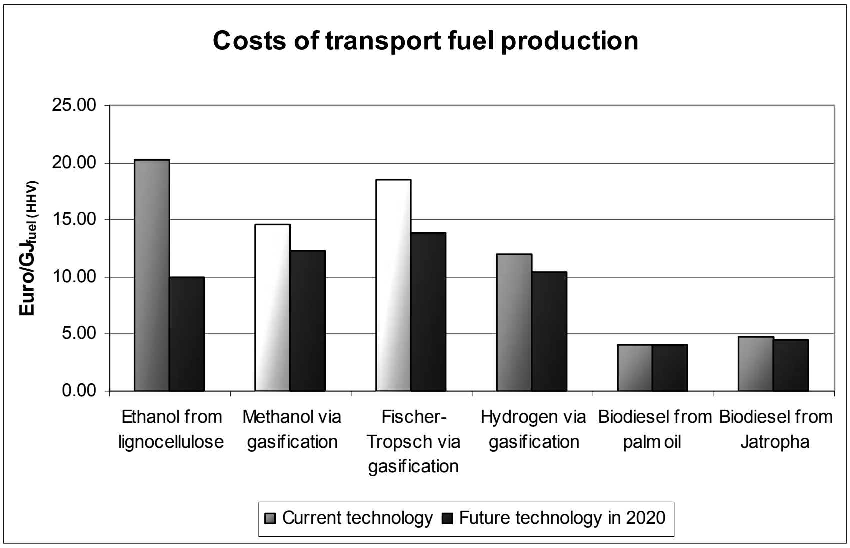
7 Accounting for the energy input from methanol, the net efficiencies of palm diesel and jatropha diesel production becomes 0.95 MJ_{fuel}/MJ_{HHV} and 0.91 MJ MJ_{fuel}/MJ_{HHV}), respectively.

Table 5: Input data for conversion to transportation fuels (based on data from Faaij, 2006a/b, Hamelinck and Faaij, 2006)

Transport fuel	Time	Capacity (MW_{fuel})[a]	investment costs (€/kW_{fuel})[b]	O&M costs (% of investm.)	Load factor (h/yr)	Net fuel efficiency (MJ_{fuel}/MJ_{HHVo})	By-products	Price by-products
Ethanol from lignoc.	Now	140	2085	6.4	8000	0.35	0.04 MJ_e/MJ_{bio}	0.0083 €/MJ_e
Ethanol from lignoc.	2020	950	230	3.6	8000	0.47	0.04 MJ_e/MJ_{bio}	0.0083 €/MJ_e
Methanol	Now	200	1255	4	8000	0.55	0 MJ_e/MJ_{bio}	0.0083 €/MJ_e
Methanol	2020	1000	1104	4	8000	0.48	0.12 MJ_e/MJ_{bio}	0.0083 €/MJ_e
Fischer-Tropsch liquids	Now	180	1600	4	7500	0.45	0 MJ_e/MJ_{bioV}	0.0083 €/MJ_e
Fischer-Tropsch liquids	2020	900	1200	4	7500	0.45	0.1 MJ_e/MJ_{bio}	0.0083 €/MJ_e
Hydrogen via gasification	Now	250	800	4	7500	0.6	0 MJ_e/MJ_{bioV}	0.0083 €/MJ_e
Hydrogen via gasification	2020	1100	655	4	7500	0.55	0.06 MJ_e/MJ_{bioV}	0.0083 €/MJ_e
Biodiesel from palm oil	Now	70	112	5	6000	1.0	0.003 $kg_{glycerine}$/ MJ oil	0.05 €/$kg_{glycerine}$
Biodiesel from palm oil	2020	150	100	5	7000	1.0	0.003 $kg_{glycerine}$/ MJ oil	0 €/$kg_{glycerine}$
Biodiesel from jatropha	Now	10	195	7	6000	1.0	0.003 $kg_{glycerine}$/ MJ oil	0.05 €/$kg_{glycerine}$
Biodiesel from jatropha	2020	180	170	5	7000	1.0	0.003 $kg_{glycerine}$/ MJ oil	0 €/$kg_{glycerine}$

Figure 6: Resulting transport fuel costs at biomass fuel costs including transportation of EUR 4.5/GJ_{HHV} for lignocellulosic crops and EUR 3.5/GJ_{HHV} for vegetable oils using basis assumptions: lifetime of 20 years and interest rate of 6% and an electricity price of EUR 0.03/kWh.



Discussion

63. The data presented in this dataset have been derived from various sources. Parameters show broad ranges because of different methodologies, different technological and management concepts assumed, different assumptions on technological learning and different regional circumstances. As a consequence, cost data are not be completely comparable as different assumptions might have been used in the studies, for example on including engineering into the calculation of investment costs. However, it should be noted that cost data presented refer to direct cost and do not include externalities that take into account environmental impacts. Moreover, cost data are in general derived from bottom-up engineering calculations, which are not always derived from cost data from commercial operation.

64. Especially land rents, biomass production systems and partly logistics depend on regional characteristics and can be very location specific, i.e. even within one country parameters like biomass yields, costs of transport to a central location or biomass production cost can vary considerable. Therefore, data in this report are estimates of about average situations but are not suitable to assess the situation for specific locations. As land rents vary widely through different regions and few estimates of agricultural land rents are available, the land rents used in this report are rough regional estimates. Ideally, more detailed land rents that change with increasing demand for agricultural products would be used in modelling.

65. For future data, the achievable technological developments and cost reductions through learning and up-scaling are uncertain and estimates show large ranges in particular for concepts including gasification and 2nd generation biofuel production. While data selected show are within these ranges and can be assumed to be reasonable estimates for more generic data, costs of energy for very specific concepts can, thus, vary.

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APPENDIX: RANGES OF BIOFUEL COSTS

Table A1: Comparison of biofuel production costs using different references that assume different technological concept. (Furthermore, assuming biomass costs of 3 €/GJ_{HHV}, a rent of 6% and a lifetime of 20 years.)

	Hamelinck and Faaij, 2006	Faaij, 2006a	Smeets et al., (draft)[a]
Ethanol from lignocellulose now	18.6	9.7	16.0
Ethanol from lignocellulose 2020	6.6	6.1	12.2
Methanol via gasification now	10.1	11.0	11.9
Methanol via gasification 2020	6.0	9.0	10.5
Fischer-Tropsch via gasification now	14.7	14.2	19.6
Fischer-Tropsch via gasification 2020	7.6	10.5	17.1
Hydrogen via gasification now	12.9	8.8	12.4
Hydrogen via gasification 202	4.5	8.5	10.0

[a] Based on the JRC well-to wheels study.

ABBREVIATIONS

AEZ: agro-ecological zones
BFB: bubbling fluidized bed
BIG: biomass integrated gasification
CC: combined cycle, i.e. production of electricity with a combination of gas turbine and steam turbine
CFB: circulating fluidized bed
CHP: combined heat and power
CPO: crude palm oil
h: hours
ha: hectare
HHV: higher heating value, i.e. heating value with recovery of latent heat in vaporized water
LHV: lower heating value, i.e. heating value without recovery of latent heat in vaporized water
kW_e: kilo Watt electric
kWh: kilo Watt hour (1 kWh=3.6 MJ)
kW_{th}: kilo Watt thermal
Mg: Mega gram (1 Mg = 1 metric tonne)
Mg_{od}: Mega gram (1 Mg = 1 metric tonne) oven-dried material
MJ: Mega Joules
MJ_{bio}: Heating value of biomass in Mega Joules
MJ_e: Mega Joules electric
MJ_{th}: Mega Joules thermal
MW: Mega Watt
MW_e: Mega Watt electric
MW_{th}: Mega Watt thermal
O&M: operation & maintenance
od: oven-dry, i.e. without moisture
yr: year

GLOSSARY

Afforestation: Establishment of a new forest by plantation.

Agro-ecological zones: Zones that describe the suitability of an area for crop production based on a combination of climatic and soils characteristics.

Bioelectricity: Electricity produced using biomass as fuel

Bioenergy chain: Life cycle of bio-energy production, including biomass production, transportation, pre-treatment and conversion.

Biofuels: Transportation fuels from biomass

Bioheat: Heat produced using biomass as fuel

Biomass integrated gasification with combined cycle: Power generation technology where biomass is gasified and the resulting synthesis gas is in a combined cycle, i.e. the gas is first used in gas turbine and the resulting waste heat is then used in a steam cycle.

Biomass yield: Amount of biomass that can be harvested from an area of land.

Biomass: Organic matter; biomass includes residues from forestry and agriculture, common agricultural crops, fast growing energy crops, wood, wastes from processing food and wood products as well as organic municipal wastes.

Briquetting: Mechanical process of compacting biomass into briquettes, i.e. blocks of biomass comparable in size to coal briquettes.

Co-firing: Combustion of fossil fuel and biomass at the same time in a power plant.

Co-gasification: Gasification of fossil fuel and biomass at the same time in a gasifier.

Combined heat and power production: Simultaneous production of heat and power in a power plant by using waste heat from electricity production.

Crude palm oil: Oil that is derived by extraction from the fruits of oil palms and that has not been further refined.

Ethanol: Alcohol, that is usually produced from fermentation of biomass. Ethanol can be used as transportation fuel as well as for human consumption.

Fischer-Tropsch diesel: Synthetic transportation fuel that can be produced from the conversion of natural gas as well as from the conversion of synthesis gas derived from the gasification of biomass.

Fluidized bed combustion: A method of burning particulate fuel in which the fuel together with an inert bed material acts like a turbulent fluid in the boiler. Fluidized beds have long been used for the combustion of low-quality, difficult fuels.

Gasifier: Equipment used for gasification, i.e. the conversion of solid fuels into gas.

Glycerine: By-product of biodiesel production that can be used among others in the cosmetic industry.

Grate firing: Combustion technology used in power plants. During combustion a solid fuel (e.g. biomass) is placed on a grate within the boiler.

Heating value (higher/lower): The heating value of a fuel is the amount of heat released during combustion. The lower heating value assumes the latent heat of vaporization of water in the fuel is not recovered by condensation, while the higher heating values assumes the recovery of this latent heat.

Hydrolysis: Chemical reaction adding water that can be used to break-down polymers, e.g. lignocellulose.

Jatropha: A tropical bush with oil-containing seeds. Jatropha oil is non-edible and often used for bio-energy purposes.

Lignin: Complex natural polymer that is a major component of lignocellulose. Lignin is a major structural element grass and wood.

Lignocellulosic biomass: Biomass that consists mainly of a combination of lignin and cellulose. Lignocelluloses biomass is derived from grasses as well as from wood.

Load: The amount of time a power plant is operated at full capacity operation.

Methanol: Alcohol, that can be produced via various processes, e.g. from the synthesis gas resulting from the gasification of biomass. It can be used as transportation fuel but is toxic for human consumption.

Miscanthus: Fast growing tropical grass species that is used as perennial biomass crop.

Net annual increment: Average annual volume of gross increment over the given reference period minus mortality of all trees. The gross annual increment describes the natural growth in a year.

Palm kernel expeller: By-product from palm kernels after oil has been extracted from them.

Palm kernels: Seed of the oil palm that is inside the fruit.

Panamax: Ship with dimensions that allow it to pass through the Panama canal, i.e. with a capacity of about 63000 tonnes.

Pelletising: Mechanical process of compacting biomass into small pellets with typical sizes of several mm.

Perennial grass: Grass that last for several seasons, i.e. that does not have to be re-established annually.

Press cake: By-product from oil plants, after oil has been extracted, i.e. pressed.

Short rotation forestry: Forest plantations that are harvested in short time intervals, often about every 3-4 years. For example, willow and eucalyptus are tree species that are planted in short rotation forestry systems.

Transesterification: Conversion of an organic acid ester into another ester of that same acid that is used for the production of alkyl esters from vegetable oils. These alkyl esters can be used as biodiesel.

Wood chipping: Process of reducing larger parts of wood into small pieces with typical sizes of several cm.

Conversion Factors

General Conversion Factors for Energy (Source: IEA)

To: / From:	TJ	Gcal	Mtoe	MBtu	GWh
	Multiply by				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

Conversion Factors for Mass (Source: IEA)

To: / From:	kg	t	lt	st	lbh
	Multiply by				
kilogram (kg)	1	0.001	9.84×10^{-4}	1.102×10^{-3}	2.2046
tonne (t)	1000	1	0.984	1.1023	2204.6
long ton (lt)	1016	1.016	1	1.120	2240.0
Short ton (st)	907.2	0.9072	0.893	1	2000.0
Pound (lb)	0.454	4.54×10^{-4}	4.46×10^{-4}	5.0×10^{-4}	1

Conversion Factors for Volume (Source: IEA)

To: / From:	gal U.S.	Gal U.K.	bbl	ft^3	l	m^3
	Multiply by					
U.S. gallon (fal)	1	0.8327	0.02381	0.1337	3.785	0.0038
U.K. gallon (gal)	1.201	1	0.02859	0.1605	4.546	0.0045
Barrel (bbl)	42.0	34.9	1	5.615	159.0	0.159
Cubic foot (ft^3)	7.48	6.229	0.1781	1	28.3	0.0283
Litre (l)	0.2642	0.220	0.0063	0.0353	1	0.001
Cubic metre (m^3)	264.2	220.0	6.289	35.3147	1000.0	1

Fuels Characteristics: (Source: Hamelinck, 2004)

	Density (kg/m3)	**Heating value** ($GJ_{LHV}/tonne_{wet}$)	($GJ_{HHV}/tonne_{dry}$)
Gasoline	740-750	43.2 – 43.7	47.3
Diesel	810-860	41.9 – 43.1	45.2
Ethanol	791	26.4	29.8
Methanol	791	19.8	22.9
Hydrogen	70.8 (liquid), 0.0848 (gas)	120	143
Fischer-Tropsch diesel	770	42.9	46.4