The Economic Viability of Wood Energy Conversion Technologies in Germany

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Abstract

Considering the ambitious goals to increase the share of renewable energies in the heat, power and transport sector, wood energy plays an important role in Germany´s energy transition. However, various wood market outlooks and scenarios describe the limitations of wood mobilization in Germany. This could result in rising wood prices, as well as in higher competition among wood fuel consumers.

In that context, this paper deals with the question of which wood energy conversion pathways are most competitive in Germany. With regard to the feedstock prices, the competitiveness of various wood fuel conversion pathways is assessed. Applying the concept of ceiling prices, combined heat and power plants are relatively vulnerable to increasing wood prices. The ceiling prices of synthetic biofuels already reach high levels. However, their market entry depends on many other aspects. If fossil fuel prices continue to rise, heat provision from woody biomass remains a very attractive option in Germany. But different types of wood fractions are suitable as wood fuels, and an analysis of wood fuel qualities and prices provides more insights in the economic viability of wood energy pathways and their possible role in Germany´s energy transition.

Keywords: bioenergy, competition, wood demand, wood supply, ceiling price.
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Introduction

In Germany, various political measures and high oil prices have created an effective set of incentives to utilize wood fuels in recent years. In terms of final energy, wood's share (including small volumes of other solid biomass) amounts to 66% of all bioenergy today (Böhme et al. 2011). Owing to the ambitious targets for renewable energies within the climate and energy program of the German government, the contribution of wood fuels, in terms of volume, to the heat, electricity and transport market is expected to increase further (Nitsch 2008). At the same time, an increasing number of shortages in wood supply, both in physical and economical terms, have been recently reported (Bardt 2008, Bringezu et al. 2008, Schulte 2007).

This fact has induced research in that area with a focus on the future wood supply and demand in Germany. Integrating the climate and energy targets on the demand side and ongoing trends on the supply side, an imbalance is predicted by various research groups (Dieter et al. 2008, Mantau et al. 2010, Mantau et al. 2007, Thraen et al. 2009). With regard to scarcity of natural resources, economic theory offers approaches to this issue both on the supply side—extension of resource base—and on the demand side—e.g., substitution of wood and/or addition by other biomass, further technical progress and/or a decline in demand (Endres and Querner 1993, Hackett 2006). Approaches to increase future wood supply and to reduce wood demand have considerably been discussed and described (Galembert 2007, Hetsch 2009, Mantau et al. 2010, Mantau et al. 2007, Schulte 2007, UNECE/FAO 2011). However, particular information about the consequences of wood scarcity on the economic viability of wood energy conversion technologies is lacking.

Since the results of various wood market outlooks motivated the research of that paper, in a first step, wood demand and supply scenarios for Germany are introduced and discussed. Based on the findings of these scenarios, wood energy conversion pathways are described with regard to their competitiveness. Therefore, the concept of ceiling prices is applied to the wood energy pathways (Henniges 2007, Schmidhuber 2006), describing their maximum purchasing power for wood fuels. Finally, these ceiling prices are analyzed in combination with present wood fuel prices. Thus, the economic viability of wood energy for the heat, power and transport sector is analyzed.

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Future Wood Availability

Recently, various wood market outlooks for Europe and, especially, Germany (Dieter et al. 2008, Hoefnagels et al. 2011, Mantau et al. 2010, Mantau et al. 2007, Thraen et al. 2011, Thraen et al. 2009, UNECE/FAO 2011, Pöyry 2011) have been published. Although data on wood resources and the methods applied are not consistent, the conclusion of these studies is more or less the same: It will be a challenge to balance wood supply and demand in the year 2020 and beyond.

The most common approach describing the supply side is material flow modeling that is based on simulations of forest growth and harvesting activity. To comply with sustainable forestry management, criteria such as the net annual increment with regard to the social and ecological optimal age class structure of the forests, and the maximum sustainable harvest level, are considered (EEA 2006, Hetsch 2009, UNECE/FAO 2011). Most studies include wood flows from outside the forests, such as wood-processing residues, post-consumer recovered wood, wood from parks and road maintenance, etc. Data on imports and exports of raw wood and timber products have improved in recent years, but modeling wood energy trade is still in its infancy (Hoefnagels et al. 2011, Hillring and Trossero 2006, UNECE/FAO 2011).

The EUwood study (Mantau et al. 2010) states that wood supply exceeds demand in the year 2010. According to different wood market scenarios, the German wood potential ranges between 1,080 and 1,700 peta Joule (PJ) in the year 2020 (Figure 1). The wood energy scenarios DBFZ (Thraen et al. 2011) and EFSCO energy (UNECE/FAO 2011) reference have the highest wood supplies. In comparison, the scenarios DBFZ environment and EFSCO reference are characterized by higher environmental standards, lowering the wood potentials. Considering the differences of these scenarios, the highest uncertainties result from the following issues:

- forest wood mobilization with regard to nutrient cycles, forest area designated for conservation, mobilization of small forest owners
- data and approaches for the assessment of wood from landscape management
- yield and volume of SRC
- import and exports of wood

Without the highest and the lowest wood availability scenarios, the potential for woody biomass is between 1,200 PJ and 1,400 PJ in 2020. The underlying assumptions of the scenarios that are within this range can be estimated as rather realistic.

Qualities and Prices of Wood Energy Carriers

The aforementioned wood potentials are the sum of wood fractions from different origins and qualities. The price for different wood energy carriers and qualities ranges from 0 euro (€) per giga Joule (GJ) to as much as 21 €/GJ (Figure 2). The reasons for these large price deviations can be differences in conditioning, quality, amount delivered, certification, transport distances or regional market structures (CARMEN 2012a,b,c; DBFZ 2011; Hoefnagels et al. 2011; Sikkema et al. 2011; Thraen et al. 2012; TFZ 2012).

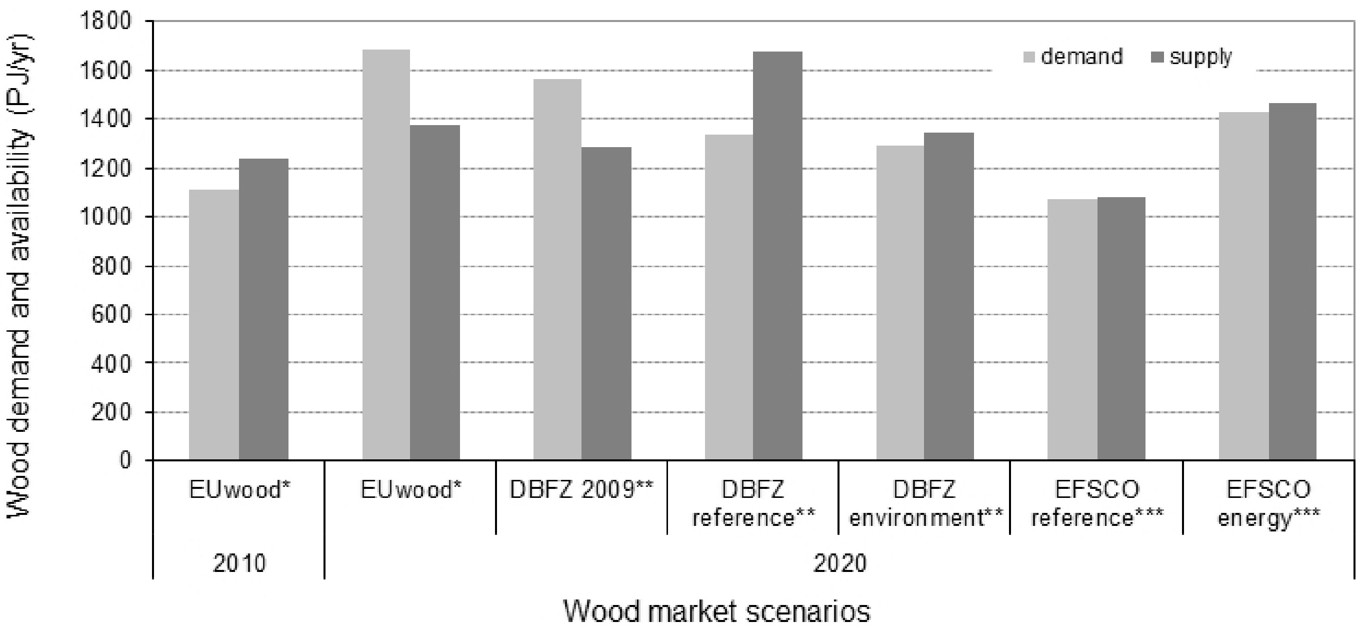

Figure 1. *Wood balance 2010 and wood market scenarios for 2020. Abbreviations and sources: *EUwood from Mantau et al. (2010), **DBFZ (Deutsches Biomassforschungszentrum) from Thraen et al. (2009 and 2010), ***EFSCO (European Forest Sector Outlook) from UNECE/FAO (2011).*

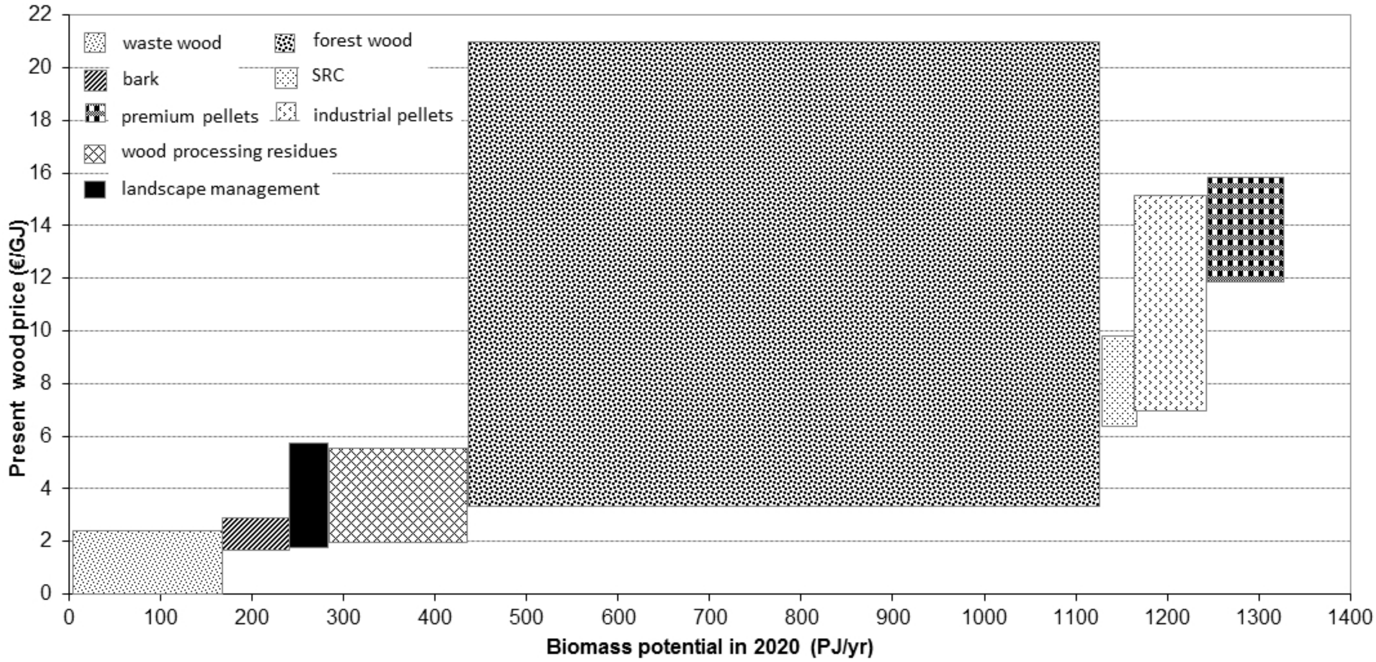

Figure 2. *Present price ranges and 2020 biomass potential of different woody biomass energy carriers. The horizontal lines of boxes indicate the minimum and maximum wood prices reported by different institutions. The width of the boxes indicates the biomass potential of the wood energy carriers. Biomass potentials are according to EUwood 2020 (Mantau et al. 2010), DBFZ environment scenario (Thraen et al. 2011 and Hoefnagels et al. 2011). SRC = short rotation coppice.*

If no other source is cited, the biomass potentials relate to the EUwood assessment for the year 2020 and are as follows:

- **Waste wood** refers to fractions of used wood from packaging, demolition wood or municipal waste. Hence, the wood categories differ in treatment such as untreated or treated with paint, glue, or preservatives. The promotion of waste wood within the Renewable Energy Sources Act made Germany a net importer of waste wood in recent years (Thraen et al. 2012). Due to a decreasing amount of waste wood that is landfilled in the future, the biomass potential is projected to increase little to 83 PJ in 2020 (Mantau et al. 2010). According to the different qualities, waste wood prices are between 0 and 2.4 €/GJ inclusive of transportation costs in 2010. In some cases, even a premium for the waste wood incineration is paid (Thraen et al. 2012).

- The biomass potential of **bark** is about 30 PJ in 2020. Bark is a by-product at saw and paper mills that is often internally utilized as a feedstock for the provision of process heat. No market price is known. A collection of price data ranges from 1.8 to 2.9 €/GJ in 2010 inclusive of short distance transportation (DBFZ 2011).

- **Wood from landscape management** has become relevant with the amendment of the Renewable Energy Sources Act in 2009 in Germany. Then, a bonus for the power production of certain wood from landscape management was introduced. For example it comprises wood from maintenance measures in public and private parks, along road-, rail- and waterways, or gardens. The assessment within the EUwood project amounts to 49 PJ in 2020. No Germany-wide market price for wood from maintenance operations yet exists. From a number of suppliers, prices for wood chips have been reported between 1.9 and 6.8 €/GJ regional transportation inclusive (Witt et al. 2011).

- The largest amount of **wood-processing residues** derives from sawmills. The share of sawmill by-products is almost 40% of the roundwood equivalent (Mantau et al. 2010). It comprises slabs chips and sawdust. In 2010, the prices for sawdust varied between 3.8 and 5.5€/GJ without delivery (Thraen et al. 2012). Together with other industrial wood residues, the total amount of wood-processing residues is estimated at 210 PJ in 2020 (Mantau et al. 2010).

- **Forest wood** contributes most to the wood biomass potential in Germany. According to the EUwood medium mobilization scenario, 689 PJ of stemwood can be removed in the year 2020. Another 184 PJ/year are forest residues. A large amount of forest wood is utilized as wood logs. The price for wood logs refers to 33 centimeters large cuttings and ranges from 6.9 €/GJ to 21 €/GJ delivered within a radius of 10 kilometers (km) (TFZ 2012). Wood chips from forests are made from stemwood, as well as from branches and tree tops. The minimum price is 3.4 €/GJ for a quantity of 80 cubic meters of wood chips with a water content of 35%; the maximum price reached is 10.5 €/GJ 2012 (CARMEN 2012a).

- The commercialization of **short rotation coppices (SRC)** is about to start in Germany (Plieninger et al. 2009, Schoene 2008). Today the area under cultivation is about 6,000 hectares (ha) inclusive of Miscanthus and other energy plants for solid biomass production (FNR 2011). Because there is no designated agricultural area for SRC, projection of the future wood supply from SRC is quite a challenge. Different scenarios show a high potential of agricultural land for the cultivation of short rotation coppices in Germany in the year 2020 (Hetsch 2009, Nitsch 2008, Thraen et al. 2011). According to a modeling approach of Thraen et al. (2011), the biomass supply from SRC is 37 PJ and relates to 160,000 ha agricultural area in 2020. In 2012, the first collection of market prices was published for wood chips from SRC. The price difference is 6.3 to 10.0 €/GJ inclusive of transportation within a radius of 20 km (CARMEN 2012c).

- With regard to the large technical potential of biomass co-firing in Germany, a scenario for the **import potential of industrial wood pellets** complements the biomass assessment of the EUwood project. The business-as-usual scenario from Hoefnagels et al. estimates the import potential of industrial wood pellet to Germany at 84 PJ in 2020. Taking different woody raw materials, sourcing regions and logistic chains into account, the corresponding pellet prices at regional distribution centers or harbors are from 6.7 to 15 €/GJ (Hoefnagels et al. 2011).

- The potential supply of **premium pellets and briquettes from domestic production** is difficult to estimate. Therefore, Mantau et al. (2010) directly coupled the pellet supply to the national demand projections for wood pellet installations. The corresponding volume of premium wood pellets and briquettes is 87 PJ in 2020. Minimum and maximum pellet prices are 11.9 and 15.9 €/GJ, respectively, in the first quartile of 2012. The prices include delivery within a distance of 50 km (CARMEN 2012b).

Concerning upcoming long-distance international transports (Heinimö and Junginger 2009; Hillring and Trosero 2006; Junginger et al. 2009), high-energy density of woody biomass is gaining importance. It is expected that upgrading technologies such as torrefaction and pelletizing of biomass can have significant impacts on costs of supply chains and the economic biomass potential (Hoefnagels et al. 2011, Uslu et al. 2008, Verhoeff et al. 2011). Torrefaction so far is in research and demonstration status (Cocchi et al. 2011, Chum et al. 2011). Hence, it is not considered here. Thus, the abovementioned quantities, qualities and prices are not rigid and can change in the future.

Future Wood Demand

On the demand side, scenarios of material and energetic use of wood are developed. Macroeconomic indicators such as gross domestic product (GDP), demographic developments or international trade flows are usually applied to quantify the future wood demand for non-energy purposes and the activity rate in the forest sector. One shortcoming of macroeconomic indicators is the integration of new and innovative wood products in wood demand projections. But projections about innovations are difficult to quantify. A common approach is a qualitative description of possible impacts on future markets (Mantau et al. 2010, UNECE/FAO 2011).

Such a macroeconomic concept does not yet work well with wood energy demand. There is not enough historic data available to run an econometric model, and many wood plant operators secure their feedstock supply from non-market resources such as wood from gardens, landscape management or privately owned forests. Hence, most wood energy scenarios consider the relationship between support mechanisms and renewable energy targets, respectively, and the resulting wood demand. For example Mantau et al. (2010) assume that wood energies' contribution to fulfill the country-specific renewable energy targets of the EU directive on the promotion of energy use from renewable sources (EU RES Directive) will decrease from about 50% in 2008 to 40% in 2030. This, in terms of absolute figures, means an increase of heat and power supply from biomass.

Since the national renewable energy action plans (NREAP) from all 27 EU member states were aggregated and analyzed in 2011, more projections are available about the planned contribution of solid biomass and wood energy to the national renewable energy targets (Beurskens and Hekkenberg 2011). Another way is to interpolate the historic growth in wood energy into the future (Mantau et al. 2007). An additional important factor is the deployment of new technologies and conversion pathways with regard to both their expected market entry and market barriers (De Wit et al. 2009). Considering woody biomass, this concept is critical to projections of thermo-chemical and biochemical conversion pathways producing liquid and gaseous biofuels. Most studies expect these so-called second-generation biofuels to become relevant beyond 2020 (IEA 2010; Martinsen, Funk, Linsesen 2010; Thraen et al. 2011; UNECE/FAO 2011). Another wood energy conversion pathway that could have a large impact on wood markets is the co-combustion of biomass in coal plants. If considered at all, co-firing is summarized with power generation from biomass power plants.

The comparison of wood demand scenarios in Figure 1 illustrates that demand in the EUwood and the DBFZ 2009 scenario is higher than the available amount of wood resources. This is mainly due to the facts that both demand scenarios are neither balanced with the wood supply, nor consider the economics of wood energy pathways. Neglecting the interdependencies between wood demand and wood availability results in an imbalance in 2020 in Germany. Depending on these two scenarios, the theoretical imbalance between wood demand and supply is about 300 PJ (Mantau et al. 2010, Thraen et al. 2009).

The DBFZ 2011 scenarios, as well as the UNECE/ FAO European Forest Sector Outlook (EFSOS) Study II scenarios, take the interdependencies of wood availability and demand into account. Of course, the wood demand of these scenarios is lower than under less-constrained demand assumptions. As can be seen from Figure 1, the corresponding wood demands are below the wood availability in 2020.

EFSOS is perhaps the most comprehensive analysis of the future wood demand and supply in Europe at present. Here, under a "promoting wood energy scenario," the highest-possible sustainable domestic supply and wood imports from outside Europe are necessary to satisfy the demand projections. Considering the high risks to biodiversity to nutrient cycles or to the wood-using industries, this scenario shows the constraints for the future wood energy development, as well. The wood demand scenarios of Thraen et al. (2011) — DBFZ reference and environment — describe some impacts of wood scarcity on the market diffusion of wood fuel conversion pathways. The modeling is based on the economics of wood energy conversion technologies with regard to wood prices.

If and when wood energy technologies become market-relevant in the future, is difficult to quantify. But their economic performance in comparison to other technologies gives some insights in their future role.

Ceiling Prices of Different Wood Energy Conversion Pathways

In this context, the economic competitiveness is assessed with regard to the ceiling price of wood. The basis of the approach is the idea of increasing competition between different wood energy conversion pathways if shortages of wood supply arise. Wood prices are a well-accepted indicator of the scarcity of resources (Endres and Querner 1993, Hackett 2006). The various ceiling prices are calculated by applying the annuity method for a period of 20 years (with annuity factor a=0.1168). Therefore, the ceiling prices for wood (P_w) are determined by the capital expenditures ($I_i \times a$), operating expenditures ($O_i \times a$), subsidies in the form of tax reliefs or investment grants (S_i) and the revenues from heat sales (R_h) and/or feed-in tariffs (R_p). Regarding the co-firing of wood with hard coal, the savings from purchasing EU emission allowances are included, as well. In financial terms, it is the CO_2-emission avoidance (E_i) multiplied with the price of EU emission allowances at the European Energy Exchange (EEX) spot market (P_{eua}). Given all these parameters, Equation (1) describes the wood ceiling price as a function of the fossil fuel reference price (P_f).

A crucial factor is the amount of wood (X_w) required to produce the final energy heat (X_h), power (X_p) or transport fuel (X_b) from a certain amount of fossil feedstock (X_f). Considering the efficiency (η_i) of both the wood and the fossil conversion technology, this relationship can be described subject to the lower heating value of the feedstock (h_i).

$$\mathrm{X_w} \times \mathrm{h_w} \times \eta_\mathrm{w} = \mathrm{X_f} \times \mathrm{h_f} \times \eta_\mathrm{f} \qquad (2)$$

In this context, bioenergy is simplified as a perfect substitute to fossil fuel references. Thus, oil prices, and hard coal prices in the case of co-firing, are indirectly linked to the ceiling prices of wood fuels. Finally, oil price developments and their impact on the competitiveness of bioenergy conversion pathways can be derived.

Although the technical potential for the co-combustion of biomass in coal plants is huge in Germany (Hansson et al. 2009, Al-Mansour and Zuwala 2010), the co-firing is not yet a commercially viable option (Sikkema et al. 2010). A sharp increase in prices for emission allowances and coal may change the economic situation in the future (Vogel et al. 2011). Today, various European countries offer financial incentives for the co-firing of biomass with coal (Sikkema et al. 2011). In contrast, German support mechanisms for electricity generation from biomass are restricted to biomass combustion only (Hansson et al. 2009).

The condition when the costs of co-firing — the left side of Equation (3) — equal the costs of hard coal combustion in power plants is given by

$$P_w \times X_w + I_i \times a + O_w \times a = P_c \times X_c + (X_c \times e_c - X_w \times e_w) \times P_{eua} \qquad (3)$$

The term $(X_c \times e_c - X_w \times e_w) \times P_{eua}$ describes the expenditures for EU emission allowances, taking the emission factors of hard coal e_c and of wood fuels e_w into account. To date, the co-firing of 10% of wood pellets is a technically realistic volume that could be co-fired to most German coal power stations (Hansson et al. 2009). Assuming emission allowances to cost 20 € per tonne (1 tonne = 1,000 kg) of CO_2 and considering initial investment costs of 310€ for each kW installed power (Vogel et al. 2011), the wood ceiling price subject to the average hard coal price in 2011 is almost 4.8 €/GJ (see Figure 3).

In the case of biomass power plants, the revenues depend on the fixed feed-in tariffs for electricity and heat sales. Because the feed-in tariffs in Germany are fixed for a period of 20 years, the revenues for each kWh electricity are stable.

$$P_w = \frac{(P_f \times X_f + I_f \times a + O_f \times a) - (I_w \times a + O_w \times a - S_i - R_i \times a) + (E_i \times P_{eua})}{X_w} \qquad (1)$$

Table 1. *Annuity of capital and operating expenditures (1,000 €/year) for different wood energy conversion technologies and their fossil reference in brackets (data from Thraen et al. 2011 and Vogel et al. 2011).*

Expenditure type	Wood energy conversion technology						
	Pellet boiler 50kW (fossil reference)	District heating 400kW (fossil reference)	CHP [a] 0.5MW	CHP 20MW	Co-firing pellets	BtL [b]	Bio-SNG [c]
Capital ($I_i \times a$)	2.2 (1.4)	36.7 (19.2)	360	5,402	1,811	47,885	16,836
Operating expenditures (without wood supply costs) ($O_i \times a$)	1.6 (0.5)	39.1 (17.7)	263	4,609	1,460	72,687	30,132

[a] CHP = combined heat and power. [b] BtL = biomass to liquid. [c] SNG = synthetic natural gas.

The feed-in tariffs for electricity (R_p) vary depending on the utilized biomass (W_i), the installed capacity of the plant (C), the applied technology (T_i) and the generated amount of heat from cogeneration (X_h). Thus, the impact of fossil fuel prices on wood ceiling prices of biomass power plants increases with the relative share of combined heat generation (X_h/X_p). Under these conditions, Equation (1) becomes

$$P_w = \frac{I_w \times a + O_w \times a - R_p(W_i, C, T_i, X_h) \times X_p - (P_h \times X_h) \times a}{X_w} \quad (4)$$

The future heat price ($P_{h,t+1}$) is a simple correlation with crude oil prices' (P_o) change over time ($t+1$), starting at current average prices for low temperature heat ($P_{h,t}$) (<130° Celsius) of 0.03 € per kWh heat.

$$P_{h,t+1} = P_{h,t} \times \frac{P_{o,t+1}}{P_{o,t}} \quad (5)$$

Because the 0.5 MW Organic Rankine Cycle (ORC) power plant's heat output is relatively high, it benefits from rising oil prices more than the large 20 MW biomass power plant. Most large German biomass power plants sell a relatively small share of their combined heat production. This explains the steep slope of the 0.5 MW ORC power plant in comparison to the 20 MW power plant in Figure 4.

Heat-only production from wood receives little or no promotion. For example, pellet boilers smaller than 100 kW can receive an initial investment grant (S_i). From an economic point of view, investors decide between biomass heat applications, heating oil boilers or natural gas boilers or other measures like higher insulation standards. As in some rural areas, natural gas is not available—it is often a decision between heating oil and wood fuels. With this simplification, the wood ceiling price of biomass can be written as a function of heating oil prices (P_f).

$$\frac{P_w \times X_w + I_w \times a + O_w \times a + S_i \times a}{X_h} = \frac{P_f \times X_f + (I_f + O_f) \times a}{X_h} \quad (6)$$

Because the capital expenditures ($I_w \times a$) of the pellet boiler can be twice as much as the heating oil reference, investment costs are an important factor to the economics of biomass heat applications (see Table 1).

High fossil fuel reference prices make biomass heat pathways an interesting option under economic considerations. Equation (7) describes the historic relationship between heating oil prices (P_f) and crude oil prices (P_o) in Germany since 1991 (MWV 2012a). Replacing (P_f) in Equation (6) with this relationship, wood ceiling prices are a function of crude oil prices.

$$P_f = 0{,}5847 \times P_o + 16{,}86 \quad (7)$$

As illustrated in Figure 3, the impact of crude oil prices on wood ceiling prices of pellet boiler and of the 400 kW wood chip plant is strong.

As in many other European countries, a mandatory biofuel quota for gasoline and diesel is in force in Germany. This quota more or less limits the annual amount of biofuels demanded by the blending companies. Biofuel producers therefore find themselves in competition with each other to sell their biogenic substitutes for gasoline, diesel or natural gas to this limited market (De Wit et al. 2009). Synthetic biofuels are not yet market mature. But, due to their better blending characteristics and their relatively high greenhouse gas emission avoidance compared to commercial available biofuels, wood-based synthetic biofuels have some market-relevant characteristics (Chum et al. 2011). However, the bankruptcy of a German pioneer in BtL technologies gives evidence of the high technical and economic hurdles to be taken for synthetic biofuels (Kopp and Morris 2011). The synthetic biofuels' economic performance on the wood energy markets is subject to crude oil prices and the tax relief scheme under § 50 of the German Energy Tax Law until the year 2015. Hence, the wood ceiling price of transport biofuels is given by

$$\left(\frac{P_w \times X_w + I_w \times a + O_w \times a - R_i \times a}{X_b} + f\right) \times VAT = P_f \quad (8)$$

The left side of Equation (8) describes the specific production costs per liter biofuel (X_b), including revenues from by-products such as heat sales ($R_i \times a$). No energy tax (f) is in force for synthetic biofuels in Germany at the moment. But, in order to compare biofuels with its fossil transport fuel reference price at the gas station (P_f), one needs to consider the value added tax (VAT) of 19%. Again, removing (P_f) with the correlation to crude oil prices in Equation (8), biofuels´ wood ceiling prices are subject to crude oil prices.

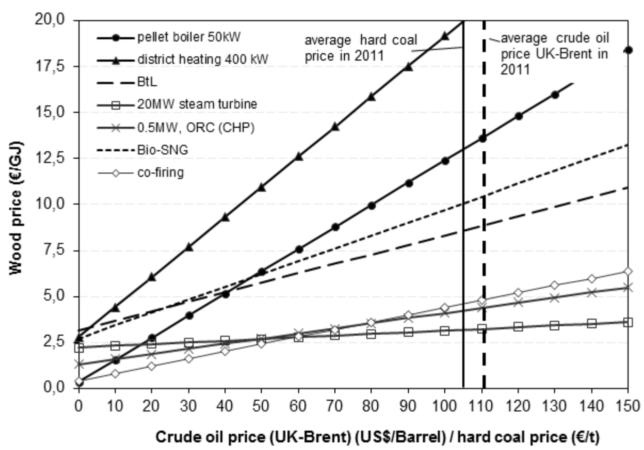

Figure 3. *Ceiling prices of different wood energy pathways subject to crude oil and hard coal price, respectively (calculations based on BAFA 2012, MWV 2012b, Thraen et al. 2011, Vogel et al. 2011).*

The wood energy conversion pathways' relationship with fossil fuels allows for a comparison of their wood ceiling prices. Subject to crude oil and hard coal prices, the ceiling prices vary considerably between the heat, electricity and transportation market (Figure 3). Owing to the relatively low share of capital expenditures on overall production costs and the good efficiency performance of applications in the heat market, their competitiveness is sharply improving with rising oil prices. A complete tax relief of 0.66 euro per liter gasoline and 0.47 euro per liter diesel creates relatively high wood ceiling prices of synthetic biofuels at low crude oil prices. High fossil fuel reference prices increase wood ceiling prices of synthetic biofuels up to more than 10 €/GJ. That is more than twice as much as biomass power plants are able to pay for their feedstocks under these considerations.

Unlike the other wood conversion pathways, the economics of co-firing depends on the prices of hard coal and of CO_2 emission allowances. In Figure 3, the ceiling price of co-firing varies subject to hard coal prices with an underlying price of emission allowances of 20 €/t CO_2. The development of the latter is highly insecure. Within the European cap and trade system, the total amount of emission allowances to be issued annually decreases by 1.74% until 2020 (European Commission 2010c). This in turn increases the likelihood of CO_2 emission allowance prices rising. The combination of high prices on coal and on carbon markets can make co-combustion of wood an attractive option for coal plant operators to reduce their CO_2 emissions (Sikkema et al. 2010).

Although this comparison of competitiveness is a simplification neglecting technical, legal and environmental limitations to wood utilization, the finding from this is evident. At year 2011 average market prices for crude oil, operators of heat boilers show the highest purchasing power on the wood energy markets. According to crude oil prices above 110 $US per barrel, liquid and gaseous biofuels can reach price parity with fossil fuels at about 10 €/GJ of wood energy carrier. Although heat production from coal plants is low in comparison with biomass power plants under EEG feed-in tariffs, co-firing realizes higher wood ceiling prices at average hard coal prices from the year 2011.

Economic Viability of Wood Energy Pathways

Besides capital costs, feedstock is the largest cost component of producing heat, power or biofuels from wood in many conversion technologies (Demirbas et al. 2009, De Wit et al. 2009, Lund and Andersen 2005). By comparing the assessed ceiling prices with the reported price ranges of wood energy carriers, the economic viability of different wood energy pathways is assessed. According to this assessment, the operation of the conversion technologies in Figure 4 is economical, if the relating feedstock prices are below their ceiling price.

At present fossil fuel prices, **wood chip heating plants** show a very high ceiling price that is above the price range of most wood energy carriers. This makes district heating with woody biomass very attractive.

The intersection of the ceiling price of **pellet boilers** with the line for the price range of premium wood pellets shows that maximum pellet prices can already be higher than the theoretical purchasing power of pellet boiler operators. As the ceiling prices react very sensitively to changes in heating oil prices, little price increases of heating oil improve the economic viability of pellet boilers very much. In comparison with the other ceiling prices, pellet boilers are a very competitive concept.

The **20 MW_{el} CHP plants´** ceiling price for the combustion of waste wood is equal to the maximum waste wood price reported in 2010. In fact, the situation for large biomass power plants is more critical than it is described in Figure 4. Many existing large CHP plants create little or no earnings from the combined heat production. Thus, their ceiling prices are usually smaller than the 2.5 €/GJ from the reference CHP plant. Waste wood price increases are likely to challenge large CHP plants in the future. But because the limits of waste wood mo-

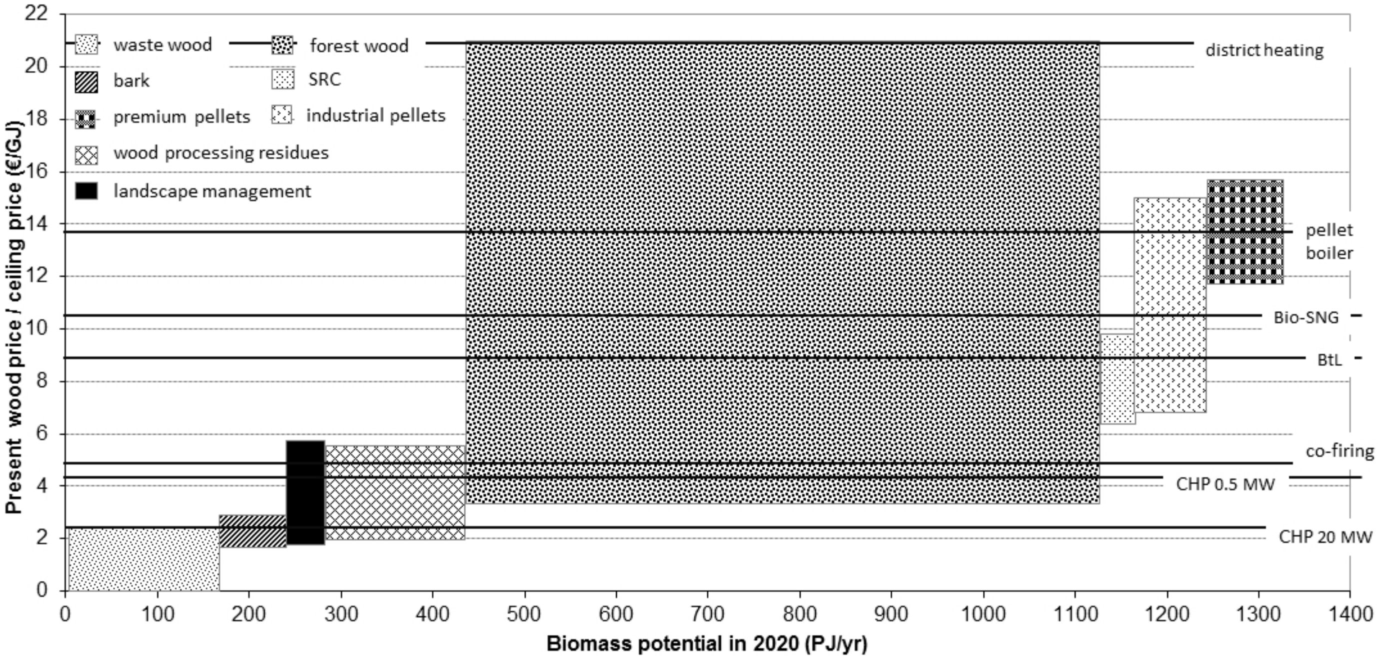

Figure 4. *Comparison of ceiling prices and price ranges of different wood energy carriers. The horizontal lines of boxes indicate the minimum and maximum wood prices reported by different institutions. The width of the boxes indicates the biomass potential of the wood energy carriers. The horizontal lines describe the ceiling prices of wood energy pathways at present fossil fuel reference prices. SRC = short rotation coppice.*

bilization have almost been reached in recent years, waste wood prices have remained at a high, but relatively stable, level (Thraen et al. 2012), confirming the concept of ceiling prices. The amendment of the EEG stopped the remuneration of waste wood fractions treated with preservatives, glue or paint for new installations beginning with the year 2012 (Renewable Energy Sources Act—EEG 2011). This could mitigate price increases and secure the competitiveness of existing CHP power plants.

The **small CHP plant** with an installed power capacity of 0.5 MW_{el} realizes a purchasing power for wood that is within the price ranges of landscape care wood and cheap fractions of forest wood. This is no surprise. The design of the remuneration according to the EEG aims at compensating plant operators for the utilization of certain woody biomass. The comparison of present ceiling prices with the market prices for forest wood and landscape care wood demonstrate that improvements are necessary to unlock the full potential of landscape care wood and certain forest wood fractions. In comparison with the other concepts, CHP plants' purchasing power is limited to wood fractions that are not demanded, or hardly demanded, by others. The reasons can be legal requirements for the combustion of treated wood fractions or technical standards for the wood fuels.

The prices for wood from SRC are about 2 €/GJ to 5 €/GJ higher than the ceiling prices relating to 0.5 MW_{el} CHP plant assessed. Higher feed-in tariffs for the combined heat and power generation from wood from SRC are in force since the beginning of 2012 (Renewable Energy Sources Act—EEG 2011). It remains to be seen if these tariffs are economical and stimulate the power generation from SRC.

At present prices for hard coal and CO_2 emission allowances, **co-firing** of industrial wood pellets is not economically viable. The present ceiling prices of almost 5 €/GJ would allow an economic substitution of hard coal with wood chips from forest residues, landscape care wood or wood processing residues. However, most German coal plants are equipped with pulverized coal-fired boilers (Hansson et al. 2009). Hence, the direct co-combustion needs preparation and milling of biomass and limits the technical potential to replace coal by wood chips to highly conditioned and dry biomass (Khan et al. 2009, VGB 2008). Today, only eight coal power plants are known that burned a total amount of 30,000 t of wood in 2010 (Bundesregierung 2011). The assessment of ceiling prices indicates that high price increases of hard coal and CO_2 emission allowances are required to create a market for co-firing in Germany.

The ceiling prices of the **Bio-SNG** and **BtL** concepts allow the utilization of high-quality wood fractions, such as industrial pellets or highly standardized wood chips. Considering the tax relief in force, these concepts are highly competitive with regard to other wood energy conversion pathways. But cutting the tax reliefs, production cost of already-established sugar or plant oil-based biofuels are lower than the theoretical production costs from synthetic biofuels at present feedstock prices (De Wit et al. 2009, IEA 2011). The planned transition to a greenhouse gas avoidance quota in the year 2015 could improve the competitiveness of synthetic biofuels. Then, the greenhouse gas abatement costs become more relevant and change the economic and environmental criteria for the utilization of biofuels. In the years to come, the development of synthetic or advanced biofuels very much depends on the environmental and economical performance of other biofuels.

High ceiling prices do not guarantee successful and economical concepts. Technical, environmental and social standards and legal requirements can increase prices of wood fuels to levels higher than some of the ceiling prices analyzed. For example, with a present ceiling price of 5 €/GJ, co-firing is far away from being an economic option to reduce CO_2 emissions in most German coal plants.

The constant high number of new wood chip applications and new pellet boilers in Germany emphasizes their economic advances (Böhme et al. 2011, Cocchi et al. 2011). Given high fossil fuel prices, the development of heat provision from woody biomass is likely to continue in the future. To what extent Germans change their heat supply depends on many criteria, such as comfort, alternative heat applications, thermal insulation and performance with regard to particulate emissions (Bundesregierung 2009, Cocchi et al. 2011, Nitsch et al. 2012).

If the wood fuel prices do not rise due to increasing production costs and/or demand from competing uses, CHP plants remain economically viable. Concerning the future development of power generation from woody biomass in Germany, under the present feed-in tariffs, the economical biomass potential for CHP plants is limited. Neglecting the highly uncertain development of SRC, CHP plants can unlock some small amounts of wood from landscape care activities and forest residues. No changes in political support assumed, technological progress, increases in efficiency and more earnings from heat sales are required in order to improve the economics of CHP plants in the future.

In the case of synthetic biofuels, the high wood ceiling prices make BtL and SNG facilities highly competitive in comparison with other wood energy pathways. However, the large volume of feedstock required for the operation of a BtL or SNG facility creates a serious market barrier. Hence, one condition for a comprehensive deployment of synthetic biofuel production in Germany is the availability of SRC or imports of highly standardized wood pellets. As long as these synthetic biofuels do not reach price parity with their fossil fuel reference, they compete with other biofuels in order to fulfill the biofuels quota. In the future, the commercial viability of biofuels depends on their greenhouse gas avoiding potential and CO_2 abatement costs in Germany. However, the future methodology for the quantification of greenhouse emissions is highly uncertain because the debate about the integration of greenhouse gas emissions from indirect land use changes (iLUC) is ongoing (European Commission 2010b, IEA 2011).

Conclusions

Germany´s decision to realize a turnaround in energy policy is accompanied by the search for solutions. Renewable energy from woody biomass is one little part of the solution. Some of the scenarios from the beginning describe how an increasing wood demand from energy provision could be met in the future. However, the economic viability of some wood energy pathways introduced is poor, and/or other reasons make their future development highly uncertain. Even if synthetic biofuels are an economically interesting concept in comparison to other biofuels, it could be more meaningful to build BtL and Bio-SNG facilities where biomass is available in large volumes and import the liquid or gaseous biofuels only.

The perspectives for the heat market are good. Most wood energy pathways can be realized without financial aid or other support mechanisms. Their contribution to the national goals for renewable energies very much depends on alternative renewable heating devices, cogeneration of heat and power, thermal insulation and their performance with regard to particulate matters.

The development of power generation from woody biomass is highly dependent on the incentives of the EEG. Under present feed-in tariffs, only a small volume of additional woody biomass could be unlocked for combined heat and power generation in the future. From an economic point of view, the wood demand from energy applications is very likely to be less than in the promoting wood energy scenarios introduced.

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