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Estimating GHG emission mitigation supply curves of large-scale biomass use on a country level

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Abstract

This study evaluates the possible influences of a large-scale introduction of biomass material and energy systems and their market volumes on land, material and energy market prices and their feedback to greenhouse gas (GHG) emission mitigation costs. GHG emission mitigation supply curves for large-scale biomass use were compiled using a methodology that combines a bottom-up analysis of biomass applications, biomass cost supply curves and market prices of land, biomaterials and bioenergy carriers. These market prices depend on the scale of biomass use and the market volume of materials and energy carriers and were estimated using own-price elasticities of demand. The methodology was demonstrated for a case study of Poland in the year 2015 applying different scenarios on economic development and trade in Europe. For the key technologies considered, i.e. medium density fibreboard, poly lactic acid, electricity and methanol production, GHG emission mitigation costs increase strongly with the scale of biomass production. Large-scale introduction of biomass use decreases the GHG emission reduction potential at costs below 50 €/Mg CO_{2eq} with about 13–70% depending on the scenario. Biomaterial production accounts for only a small part of this GHG emission reduction potential due to relatively small material markets and the subsequent strong decrease of biomaterial market prices at large scale of production. GHG emission mitigation costs depend strongly on biomass supply curves, own-price elasticity of land and market volumes of bioenergy carriers. The analysis shows that these influences should be taken into account for developing biomass implementations strategies.

Keywords: Biomass; Cost supply curve; GHG emission mitigation; Market prices; Own-price elasticity

1. Introduction

The use of biomass for energy may contribute significantly to the reduction of greenhouse gas (GHG) emissions [1,2]. It has been shown in earlier bottom-up analyses, that the use of biomass for materials combined with the energy utilisation of residues and material wastes may increase the efficiency of GHG emission reduction—i.e. increasing the amount of GHG emissions per area of land used for biomass production and/or decrease the GHG emission mitigation costs—if suitable biomass applications are selected [3,4].[1]

However, increasing the amount of biomass produced and subsequently the amount of biomaterials and biomass-based energy may lead to an increase of agricultural land prices and a decrease of material and energy prices, depending on the market volumes involved. Especially, markets for biomaterials are often quite small [5] and therefore, expected decreases of material prices are relatively large; see e.g. [6]. Market volumes and subsequent market price changes may decide which options are economically most attractive to reduce GHG emissions by large-scale introduction of biomaterials and bioenergy carriers. Furthermore, the use of agricultural land for biomass production may influence land prices significantly as the production of food and fodder on agricultural land

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[1] This increase of efficiency is in the range of avoiding about several tens of Mg CO_{2eq} per hectare and year additionally and lowering GHG emission mitigation costs about several hundreds of Euro per Mg CO_{2eq} compared to single bioenergy utilisation.

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will compete with the production of biomass for energy and materials; see e.g. [7]. As a consequence, these effects may increase GHG emission mitigation costs of biomass systems with the scale of biomass utilisation.

Various biomass supply curves have been calculated for different geographical scales; see e.g. [8,9]. These calculations were based on the availability of land and its quality and, typically, did not consider changing market prices with increased biomass production. Supply curves for GHG emission mitigation costs by carbon sequestration in forests have been determined; see e.g. [10,11]. Some of these GHG emission mitigation cost supply curves took into account that land prices increase with increasing sequestration activities. This has been done using various approaches; see the review by Richards and Stokes [12]. One of these approaches is the use of a demand curve of land that specifies market prices in relation to demand by means of own-price elasticity[2] [12]. Also the relation between the amount of biomass use and its market price has been investigated. Otto and Gallagher [13] estimated the market price of fodder by-products from ethanol production using own-price elasticity, if ethanol production is increased. De La Torre Ugarte et al. [14] calculated the demand for agricultural crops depending on their prices using a.o. own-price elasticity.

For many different options, e.g. increases of energy efficiency, carbon capture and storage, and renewable energy supplies, GHG emission mitigation costs have been calculated. These calculations were done using either bottom-up or top-down approaches including various market effects; see e.g. the review of studies in [1]. Studies considering a relation between the demand and the price of goods that use a top-down approach typically start with prices. From these prices—e.g. material prices, energy prices or carbon taxes—the demands for goods are calculated from demand curves. GHG emissions and costs of a system producing these demands of goods are then compared to those of other possible systems with different demands. Thus, various GHG emission mitigation scenarios have been developed; see e.g. [15–17].

Studies that calculate GHG emission mitigation costs of biomass systems starting from an exogenous demand, e.g. for biomass products, taking market effects into account could not be identified. Such an approach, however, may create new insights, because it could produce GHG emission mitigation cost curves for biomaterial and bioenergy application by varying the amount of biomass utilisation exogenously. Also, biomass supply curves could be integrated into the analysis, leading to overall GHG emission mitigation cost curves of biomaterial and bioenergy uses with growing biomass use considering effects on land, energy and material markets. Another advantage of this approach is that market effects for different biomass applications can be analysed explicitly, e.g. a GHG emission mitigation cost supply curve for biofuels may be different than that for biomaterials.

The objective of this study is, therefore, *to evaluate the possible influences of a large-scale introduction of biomass material and energy systems and their market volumes on market prices of land, materials and energy carriers and subsequently on GHG emission reduction costs*.

For this purpose, a methodology to estimate GHG emission mitigation supply curve for large-scale biomass use was proposed. This methodology incorporates (1) a bottom-up analysis of biomaterial and bioenergy applications, (2) scenario-dependent biomass cost supply curves and (3) market prices of land, biomaterials and bioenergy carriers depending on the scale of biomass use and on the market volume of materials and energy carriers. These market prices are estimated using own-price elasticities of demand. Because biomass supply curves as well as markets of land, materials and energy carriers depend strongly on economic development and trade, these parameters were varied for different scenarios that follow the SRES scenario families of [18].

The methodology was demonstrated for biomaterial and bioenergy use on a country level. The subject of this case study is Poland in 2015, because in the short-term new Eastern European member states of the European Union may play an important role in European biomass production, as many of these countries have relatively large areas of available agricultural land and low biomass production costs. Poland is a representative example of a Central Eastern European country with a rather high biomass production potential.

GHG emission mitigation cost curves for four selected biomaterial and bioenergy applications have been analysed. Key criteria for the selection were that the application (1) has a potentially large market volume in the year 2015, (2) potentially reduces a large amount of GHG emissions per unit of biomass used and (3) has rather low initial GHG emission mitigation costs. Moreover, for the simplification of biomass supply curves and the calculation of GHG emission mitigation cost curves, only applications have been investigated that can use the same type of biomass, i.e. short rotation wood. From earlier reviews of GHG emission reduction of biomaterials and bioenergy carriers [3–4,6], the following four biomaterial and bioenergy applications were selected:

- poly lactic acid (PLA) with waste-to-energy recovery
- medium density fibreboard (MDF) with waste-to-energy recovery
- methanol
- electricity

2. Method

To calculate GHG emission mitigation cost supply curves, various calculation steps are necessary. The various

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[2] Own-price elasticity is the percentage change of demand divided by the according percentage change of price on the demand curve of a commodity.

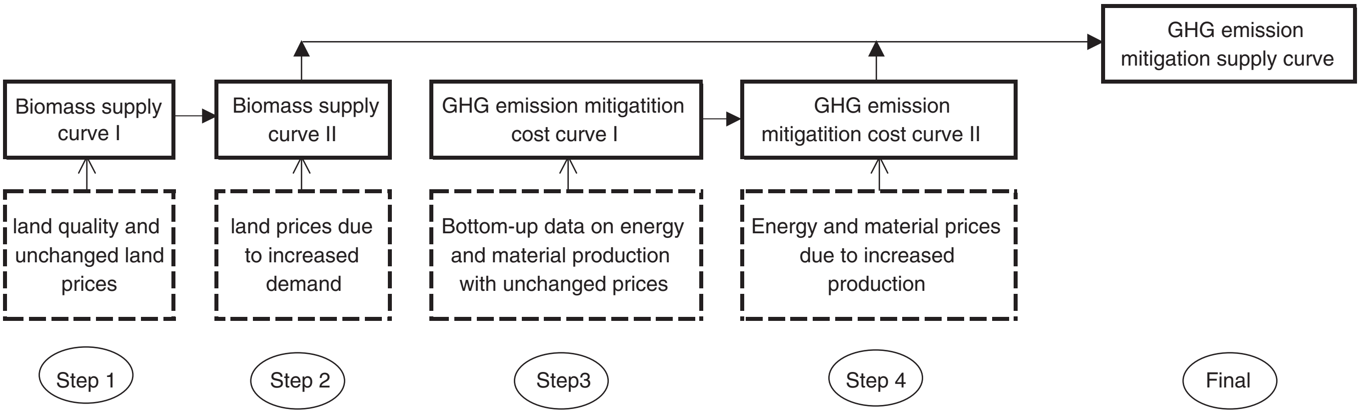

Fig. 1. Overview of the main steps to calculate GHG emission mitigation supply curves of biomaterial and bioenergy applications in which price elasticity effects are incorporated.

steps to calculate GHG emission mitigation supply curves are presented in Fig. 1:

1. Biomass supply curves describing the possible amount and costs of biomass production in Poland were determined.
2. The effects of increased biomass production on the market prices of agricultural land were investigated.
3. The GHG emission mitigation costs of selected biomaterials and bioenergy applications were calculated.
4. The changes of market prices of materials and energy carriers due to an increased production of biomaterials and bioenergy were estimated.
5. The results of these four steps were combined in a GHG mitigation supply curve.

The first step describes biomass production costs in the '*biomass supply curve I*' (€/$\mathrm{Mg_{biomass}}$). These costs are based on the biomass production costs per hectare and the available agricultural land of various qualities with different crop yields and land rents. With a growing production of biomass for energy and material applications, however, agricultural land rents are likely to rise. In step 2, these increased land rents are combined with the production costs leading to the *'biomass supply curves II'*. Step 3 results in the *'GHG emission mitigation cost curve I'* presenting the basic GHG emission mitigation costs (€/$\mathrm{MgCO_{2eq}}$) of the biomaterial and bioenergy applications. The costs are determined from the difference between production costs and market prices of the biomaterial applications and the subsequent GHG emission reductions are calculated from the difference of emissions between a biomass and a reference application. As for the land rents, an increased production of biomaterials or bioenergy may increase their market prices.[3] From these new market prices and the data from the GHG emission mitigation cost curve I, GHG emission mitigation costs as presented in the *'GHG emission mitigation cost curve II'* are calculated in step 4. Step 5 then determines the final *'GHG emission mitigation supply curve'* by summing up the biomass supply curve II and the GHG emission mitigation costs curve II. GHG emission mitigation supply costs are calculated as marginal costs to avoid an additional unit of GHG emissions, see Eq. (1). By comparing the marginal GHG emission mitigation costs of the different biomass application and selecting the respective lowest costs at each additional amount of biomass used, an overall GHG emission mitigation cost supply curve can be composed:

$$C_{\mathrm{GHG}}(S) = (C_{\mathrm{bios}}(S) + C_{\mathrm{land}}(S) + C_{\mathrm{bioa}} - R_{\mathrm{bioa}}(S))/(-GHG_{\mathrm{bios}} - GHG_{\mathrm{bioa}} + GHG_{\mathrm{sub}}). \tag{1}$$

C_{GHG} is the marginal costs of GHG emission mitigation (€/kg $\mathrm{CO_{2eq}}$), S is the scale of biomass system ($\mathrm{kg_{biomass}}$/yr), $C_{\mathrm{bios}}(S)$ is the marginal costs of biomass production in relation to scale due to the quality of available land (€), $C_{\mathrm{land}}(S)$ is the marginal costs of agricultural land in relation to scale due to land demand (€), C_{bioa} is the marginal costs of the production of biomaterials and bioenergy (€), $R_{\mathrm{bioa}}(S)$ is the revenues of biomaterial and bioenergy sales in relation to the market size and their subsequent market prices, $\mathrm{GHG_{bios}}$ is the GHG emissions during biomass production (kg $\mathrm{CO_{2eq}}$), $\mathrm{GHG_{bioa}}$ is the GHG emissions during production of biomaterials and bioenergy (kg $\mathrm{CO_{2eq}}$), $\mathrm{GHG_{sub}}$ is the GHG emissions during production of reference applications that are substituted by biomaterials and -energy (kg $\mathrm{CO_{2eq}}$).

Biomass supply curves as well as the bioenergy and biomaterial markets depend strongly on the trade of food,

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[3] An increased production of a good typically leads to a decrease in market prices, because selling the additional production necessitates an additional demand and the correlation between demand and market prices

(*footnote continued*)
is usually negative. However, if an additional demand can be created without lowering market prices—e.g. by substituting fossil reference energy carriers—market prices may also stay constant, see Section 2.4.

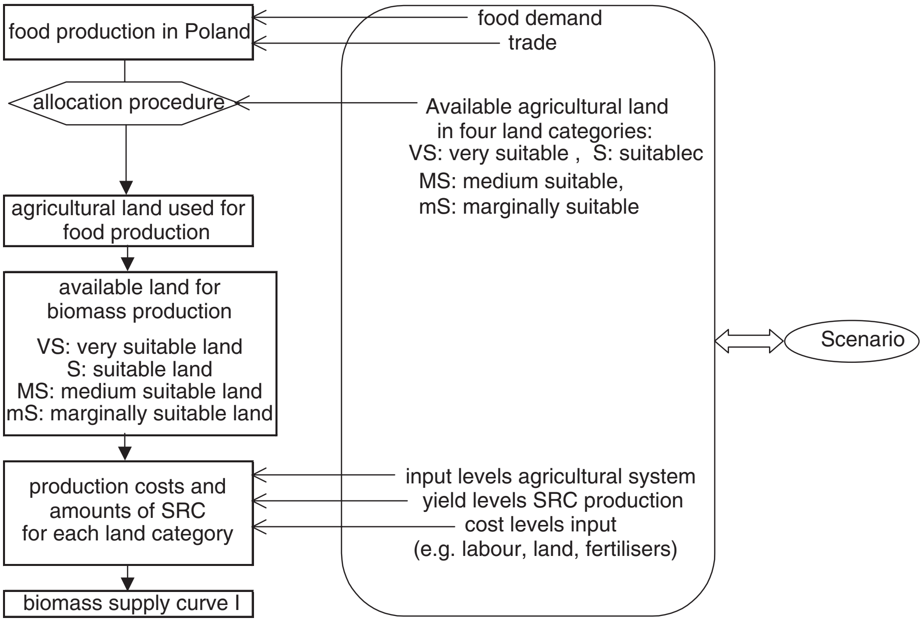

Fig. 2. Schematic overview of the calculation of biomass supply curves I.

materials and energy and technological developments in the agricultural sector, which are difficult to predict. To accommodate this variability in a bottom-up calculation, biomass supply curves and market developments were differentiated for four scenarios that reflect possible political developments in Eastern Europe. The methodology used in the various steps of this approach is discussed below.

2.1. Biomass supply curve I

The biomass supply curve I was estimated for the production of short rotation coppice (SRC) in Poland for 2015.[4] The methodology for the calculation of this biomass supply curve I is summarised in Fig. 2. Food demand and international trade determine the demand for food production in Poland. The available agricultural land in Poland was divided into four quality categories with subsequent different crop yields and land costs. These categories were: very suitable (VS), suitable (S), medium suitable (MS) and marginally suitable (mS). This agricultural land was allocated to food production in order to achieve a most efficient land use in terms of total hectares; see [30].[5] Next, agricultural land that is available for energy crop production in the four different quality categories, i.e. land that is not used for food production, was determined. From the available land,[6] biomass yields, land costs and assumptions on the agricultural production system, amounts and costs of biomass production were calculatedand summarised in the biomass supply curve I.[7]

Because agricultural production and the demand for food are strongly related to economic and demographic trends, the biomass supply curve I was determined for four different scenarios. These scenarios are related to the SRES emission scenarios [18] and are translated for Europe. The scenarios differ with regard to an economic (V1, V2) versus an environmental orientation (V3, V4) and with regard to a global (V1, V3) versus a regional orientation (V2, V4). Main characteristics of the scenarios and the most important assumptions for the calculation of biomass supply curves are presented in Table 1. (In brackets the most closely related SRES scenario family is indicated.)

2.2. Biomass supply curve II

The costs of biomass in the initial biomass supply curve I were calculated using fixed land prices differentiated by the quality of the agricultural land and varying with each scenario. In the biomass supply curve II, account was taken of the relation that the price of agricultural land increases if the demand for land increases, e.g. due to the production of biomass.

In an ideal market, the price of a good, e.g. agricultural land, and the demand for it are related negatively.

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[4] The methodology and the data used to estimate the biomass supply curves I are based on research on possible future biomass supplies in Central Eastern Europe (CEE) carried out at the Copernicus Institute, Utrecht University. This research was carried out in the context of the European Commission supported research project: *VIEWLS—Clear Views on Clean Fuels, Data, Potentials, Scenarios, Markets and Trade of* Biofuels (NNE5-2001-00619).

[5] Note, that the suitability of land is crop dependent.

[6] In the V1 and V4 scenarios, also a small part of agricultural land was reserved for the growth of forestry and urban areas. In the V3 scenario, part of agricultural land (0.5% per land suitability type) was reserved for energy crops before the allocation procedure.

[7] Input data on available land, biomass yields and production costs are summarised in Table 3.

Table 1
Characteristics of scenarios for the analysis of biomass supply

Characteristic	V1 (A1)	V2 (A2)	V3 (B1)	V4 (B2)
Main economic characteristic	Fast growing economy, international trade	Slow economy, CEE lacks behind Western Europe	EU economy, scenario based on CAP reforms	EU economy, high level of self-sufficiency in protected market
Trade of agricultural products	Liberal trade on world market	Market oriented CAP reform	Market oriented CAP reform	Self-sufficiency, import reduced substantially
Agricultural production system	High-tech advanced	Intermediate	High input	High-tech advanced
Machinery and labour input	Advanced machinery, low labour input	Current situation CEE	SOTA machinery, low labour input	SOTA machinery, low labour input
Yield levels SRC	+30% of high input system yields	−30% high input system yields	high input system (Data from IIASA)	+30% of high input system yields
Cost level production inputs	Decrease of EU prices (increased competition)	Current cost levels CEE	Current cost levels EU	Increase of EU prices (protected market)
Land costs	Current land rents USA (open market)	Current land rents CEE	Current land rents EU	Increase of EU prices (protected market)
Labour costs	Increased costs (strong economy)	Current cost levels CEE	Current cost levels EU	Increased costs

SRC, short rotation coppice; CEE, Central Eastern Europe; CAP, Common Agricultural Policy of EU; SOTA, State of the Art; IIASA, International Institute of Applied System Analysis.

This relation can be described by a demand curve. The ratio between the percentage change of demand and the percentage change of price is the so-called own-price elasticity. This own-price elasticity can vary for different demand levels of a good, but often demand curves are simplified by assuming constant own-price elasticity. This assumption was used in this analysis, too; see Eq. (2).

Biomass production leads to an additional demand for agricultural land apart from food production. It was assumed that at the given land rents—used for the calculation of the biomass supply curve I—all agricultural land is used for non-biomass production. Furthermore, it was assumed that the amount of agricultural land is fixed in the short term and that an increased demand for agricultural land leads to an increased price. The new price of agricultural land was calculated using the own price elasticity of land; see Eq. (3).[8] This formula describes, in fact, a movement of the original demand curve of agricultural land to a new demand curve. In this new demand curve, the demand of land for a certain price is higher than in the original one. This difference is the additional demand of land due to biomass production. The price on this new demand curve for the fixed amount of available agricultural land is higher than in the original demand curve; see also [6].

$$P_{\text{L-curr}} = C_{\text{L}} \times Q_{\text{L-T}}^{1/\varepsilon L}, \tag{2}$$

$P_{\text{L-curr}}$ is the current price of agricultural land rents [€/(ha yr)], C_{L} is constant [€(ha yr)$^{(-1/\varepsilon\text{L}-1)}$], $Q_{\text{L-T}}$ is the total amount of agricultural land available per year (ha yr), εL is the own-price elasticity of agricultural land,

$$P_{\text{L-new}} = P_{\text{L-curr}}(Q_{\text{L-T}}/(Q_{\text{L-T}} + Q_{\text{L-add-bio}}))^{1/\varepsilon L}, \tag{3}$$

$P_{\text{L-new}}$ is the new price of agricultural land rents [€/(ha yr)], $Q_{\text{L-add-bio}}$ is the additional demand for land due to biomass production (ha yr).

2.3. GHG emission mitigation cost curve I

A GHG emission mitigation cost curve I was calculated for each of the biomass applications, i.e. MDF, PLA, methanol and electricity. The GHG emission reduction was determined by comparing the biomass application system with a non-biomass reference system that fulfils the same functions. Costs were calculated from the difference between the production costs of biomaterials and bioenergy carriers and their market prices. This approach to calculate GHG emission mitigation costs and the type of input data necessary has been demonstrated in [6]. Market prices are fixed for the calculation of the GHG emission mitigation cost curves I. Because we were mainly interested in the market effects of biomaterial and bioenergy introduction instead of in the development of biomass applications, no scenario-dependent technology developments or subsidies are taken into account. Also other dynamics such as technological learning and the developments of new markets during large-scale implementation of biomass technologies are not considered; the timeframe until the year 2015 is too short for these effects to be pronounced and world markets in general are hard to predict.

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[8] In this analysis, different land quality classes were used for biomass production. As it was assumed that a demand for agricultural land in any of the classes will lead to increased prices on the whole land market, the increase of the average land price is calculated. From the new average land price and the ratio between the current average land price and the current land price of the land class, the new land price of the land class was calculated.

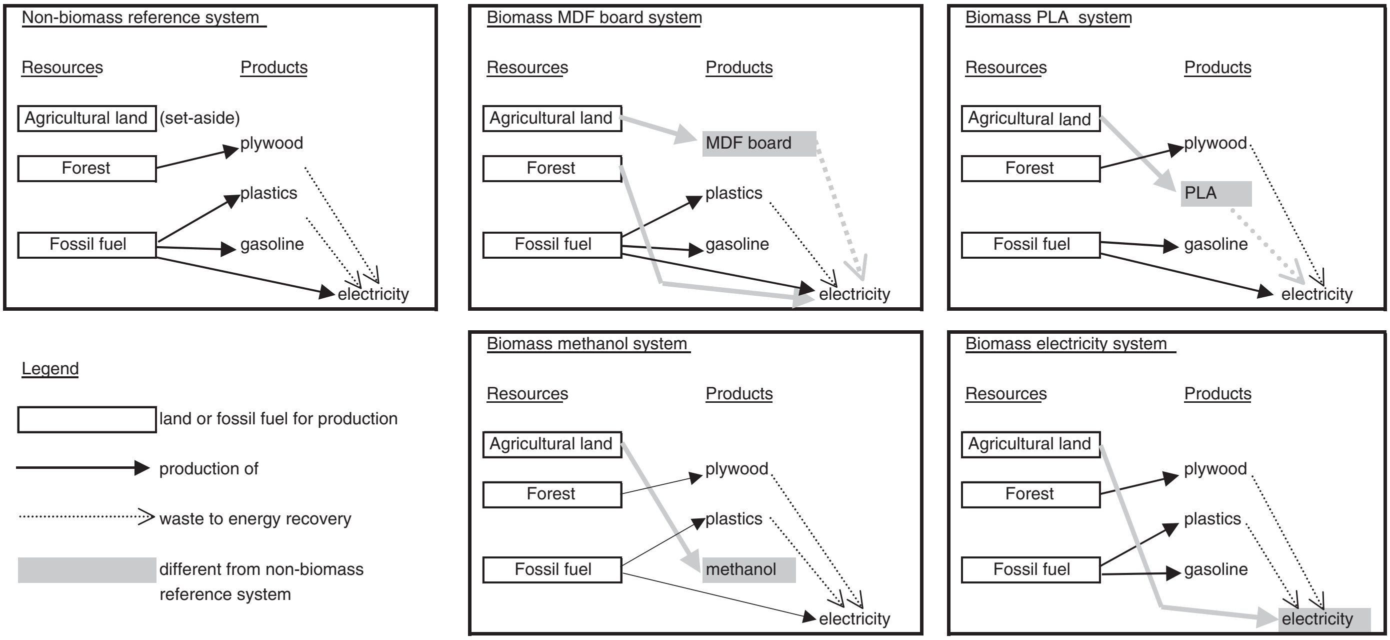

Fig. 3. Biomass systems and their non-biomass reference system.

Fig. 3 gives an overview of the biomass and reference systems considered in this study. For agricultural land, the biomass supply curves were based on the assumption that necessary food/fodder is produced and that on the remaining land biomass can be produced for other purposes. Therefore, the reference land use of agricultural land was assumed to be set-aside. In the reference system, forestry land is used for the production of plywood, which is utilised as construction material. However, if in the biomass system agricultural land is used to produce an alternative construction material, i.e. MDF board, the conventional forestry land in the reference system is used to produce wood for electricity generation.[9]

Biomaterials in the biomass system are produced and used in a 'multi-functional' way. This means that besides the biomaterials, bioenergy is produced by the utilisation of residues and waste materials. Both biomaterials and bioenergy carriers are then compared to reference materials and energy carriers. In the *MDF biomass system*, MDF board is produced from ligno-cellulosic biomass and replaces plywood from softwood produced in conventional forestry on a board volume basis. After utilisation both plywood and MDF board are incinerated with electricity recovery; see [4] for a description of MDF and plywood production. In the *PLA biomass system* bio-based PLA replaces polyethylene (PE) on a weight basis; see [6] for a description of PLA and PE production. It is assumed that both PLA and PE are incinerated for electricity recovery after use. Finally, in the *electricity and methanol biomass systems*, electricity from the grid and gasoline are replaced on the basis of energy content of the energy carriers.

2.4. GHG emission mitigation costs curve II

In the GHG emission mitigation cost curve II, market price changes of materials and energy carriers are incorporated. In an ideal market, the market price is equivalent to the marginal costs of supply and the quantities sold are equivalent to the demand at the respective market price. However, if a larger amount of a good is produced, e.g. through government interventions to reduce GHG emissions, the market price of the good will decrease until the demand equals the amount of production.

This decrease of market prices applies for the biomaterials investigated in this study, i.e. MDF and PLA. For the bioenergy carriers, i.e. methanol and electricity, the situation is different. Currently, a large amount of transportation fuels and electricity are produced from other (mainly fossil) resources. If bioenergy is produced, it substitutes the production from these sources.[10] Thus, the production of bioenergy carriers does not lead to an increased supply of energy carriers and as a consequence, market prices stay constant. However, if the total energy consumption is supplied from biomass, increased production of bioenergy carriers leads to a decrease of market

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[9] In fact, the forestry land could be used for the production of other forest products, for the production of energy, converted to agricultural land or not harvested at all. Using the assumption of electricity production, material and energy carriers in the different systems can be easily compared.

[10] This substitution depends of course on whether bioenergy carriers can compete with alternative energy carriers. In a real market, the amount of bioenergy carriers produced will be limited to the amount that can compete with other energy sources. However, in this study we want to illustrate the effect of increased bioenergy production on GHG mitigation cost and, therefore, higher amounts of bioenergy production and substitution of alternative energy carriers were investigated.

Table 2
Scenarios and their influence on the biomass energy and material markets

	V1 (A1)	V2 (A2)	V3 (B1)	V4 (B2)
Basic characteristic	Fast growing economy, international trade	Slow economy, CEE lacks behind Western Europe	EU economy, scenario based on CAP reforms	EU economy, high level of self-sufficiency in protected market
MDF market	World	CEE	World	EU-25
PLA market	World	World	World	World
Methanol market	World	World	World	World
Electricity market	EU-25	CEE	EU-25	EU-25

prices. This decrease of market prices is described in a similar way as the decrease of market prices for biomaterials. The consequences of this approach are evaluated in the sensitivity analysis.

The decrease of market prices due to an increased supply of a good can be described by a simplified demand curve with constant own-price elasticity, see Section 2.2. If the amount of biomaterial or bioenergy production is increased, the new market price of the good $P_{\text{G-new}}$ can be calculated from the total current market volume of the commodity $Q_{\text{G-T,}}$ the current price $P_{\text{G-curr,}}$ the own-price elasticity εG and the additional production of the commodity $Q_{\text{G-add-bio}}$; see Eq. (4). Also this approach has been described in [6]

$$P_{\text{G-new}} = P_{\text{G-curr}}((Q_{\text{G-T}} + Q_{\text{G-add-bio}})/Q_{\text{G-T}})^{1/\varepsilon G}, \tag{4}$$

Thus, to estimate the new market price of a biomaterial or bioenergy carrier at an increased production level, we need to know three parameters of each commodity: own-price elasticity, current market volume and current market price of the commodity.

The own-price elasticity of a good refers to a specific market, i.e. the type of good (e.g. agricultural land, forestry land) and the size of the market (e.g. only Poland or European Union). Own-price elasticity is often derived by econometric analysis from historical data on quantities sold on the market and their prices; see e.g. [19]. Two main uncertainties are inherent to this methodology. First, factors that influence the own-price elasticity—like income or the availability of goods for substitution—may be different in the future. Second, the historical data used often do not refer to the specific market investigated in our analysis, but is referring to other geographical scopes or products. For example, food demand may have been investigated instead of agricultural land demand, or global demand for gasoline may have been analysed instead of gasoline demand restricted to the European Union.

The total current market volume and market prices depend on assumptions about market size and trade. These assumptions were made for the different scenarios in accordance to the assumptions made for the production of biomass; see Table 1. Moreover, for each biomass application considered, assumptions are adapted to the specific market of that application; see Table 2. MDF board is currently traded globally, but regional markets for forest products differ as can be seen from the differences in market prices [20]. Therefore, assumptions on MDF markets in the scenarios follow the assumptions for food markets, i.e. a world market in scenarios V1 and V3 and a market limited to Central Eastern Europe and the EU-25 in scenarios V2 and V4. Plastics and transportation fuels are typically traded on a global market with global market prices. Because these commodities are usually produced from crude oil, a limitation of markets to Europe seems unrealistic. As a consequence, a world market was assumed for PLA and methanol in all scenarios. Electricity, finally, is traded on regional markets, for example within Europe, due to transportation constraints. As largest market, therefore, a market limited to the EU-25 is assumed in the V1, V3 and V4 scenarios. In the V2 scenario, the market is limited to Central Eastern Europe. Input data for market volumes and prices are discussed in Section 3.

Finally, the market volumes for Polish biomaterial and bioenergy production also depend on assumptions about the development in other countries. While the additional production of biomass applications in Poland is analysed, other countries may also increase their production. For biomaterials, this increased production of all countries in the respective market is the additional amount of production leading to a changed market price. For bioenergy carriers, the production of all these countries replaces alternative energy carriers and, finally leads to a decrease of market prices. It seems unrealistic to assume that the growth of biomaterial or bioenergy production is exclusively limited to Poland. Therefore, it was assumed that all countries increase their production of biomass applications. As an approximation for the Polish share of this increased production, we assume that the current market share of Poland for a certain good is constant.

3. Input data

3.1. Biomass supply and land markets

Background data used for the calculation of food production in the different scenarios are data on food demand, GDP growth and trade from SRES scenario projections [15,18] combined with projections from the FAO on food demands and GDP growth in Eastern Europe [21]. Yield data of agricultural crops on a grid cell level (50 × 50 km) are based on data from IIASA combined with agricultural production data from FAO and EUROSTAT statistics.

Key parameters for the production of biomass, i.e. short rotation willow, are crop yields, amounts of suitable agricultural land in Poland, land rents and biomass production costs; see Table 3. Crop yields depend on the intensity of the production system in the respective scenarios. Base data on crop yields were taken from [22–24]. The suitable areas for energy crop production are from IIASA data and have been adapted to water stresses for willow production. Land rents for Europe and the US were taken from [25–26], while Polish land rents were obtained from the Institute of Agricultural and Food Economics (IAFE) in Warsaw. Finally, production costs were calculated from a reference case of willow production on a current input level in Poland [27]. These production costs were adapted to different intensities of agricultural production and different qualities of agricultural land by assumptions on the amount of agricultural production inputs used, e.g. fertilisers based on [28] and labour based on [29].

Finally, the available agricultural land for energy production depends on the suitability of land for energy crop production and on the amount of land that is already used for food production. The available agricultural land for willow production in the different scenarios is summarised in Fig. 4 (as resulting from the bottom-up approach described in [30]).

Table 3
Key input data on biomass production in the different scenarios

	Short rotation wood yield	Suitable agricultural land for biomass production[a]	Land rents	Production costs[b]
	Mg/ha yr	Million ha	€/(ha yr)	€/(ha yr)
Scenario V1				
Very suitable land (VS)	15.0	7.20	116	314
Suitable land (S)	11.2	4.58	54	267
Medium suitable land (MS)	7.6	3.01	43	233
Marginally suitable land (mS)	2.4	2.20	25	166
Scenario V2				
Very suitable land (VS)	10.5	8.43	113	112
Suitable land (S)	7.9	3.15	35	89
Medium suitable land (MS)	5.3	3.44	29	68
Marginally suitable land (mS)	1.7	3.58	10	39
Scenario V3				
Very suitable land (VS)	12.8	7.74	165	496
Suitable land (S)	9.5	4.16	111	433
Medium suitable land (MS)	6.5	3.03	100	374
Marginally suitable land (mS)	2.1	2.13	84	303
Scenario V4				
Very suitable land (VS)	15.0	7.45	235	680
Suitable land (S)	11.2	4.41	177	601
Medium suitable land (MS)	7.6	2.93	164	528
Marginally suitable land (mS)	2.4	2.20	145	443

VS, very suitable land; S, suitable land; MS, medium suitable land,; mS, marginally suitable land.

[a] Total amount of agricultural land without subtracting land for food demands.

[b] Production costs stated here exclude land rents. The production costs are based on data from [27] in which production costs are about 281 €/(ha yr) and have been adapted for the different scenarios, characterised by different land qualities and production systems. Main assumption is that the intensive production systems require a high input of machinery and relatively less labour input. The V2 scenario is based on the current situation in Poland. Input data for the total production costs as presented in this table are: (1) interest rates, ranging from 6% for V1 to 4% for V2 [64]; (2) rotation periods (ranging from 21 years for VS land for V1 and V4 to 25 years for S land for the V2 scenario) and harvest cycle [G. Kunikowski EC-BREC, personal communication 2004, 35, 65]; (3) fertiliser use, which is related to yield levels based on the formulas from [28]; (4) cuttings per ha, ranging from 18.000 cutting/ha for S land for the V1 and V4 scenario to 12.000 cuttings/ha for S land for the V2 scenario [35,65–67]; (5) pesticide use is based on [28,35,68], and only differentiated for V2 scenario assuming a decrease of inputs; (6) fertiliser costs are € 0.44/kg for V2 (current cost level in Poland), € 0.52 for V1 (assumption is that cost levels go down with an open market compared to average EU price level because of increased competition), € 0.60/kg for V3 (average EU price level) and € 0.75/kg for V4 (assumption is that cost levels increase because of decrease of competition for European manufacturers), ranges are based on data from [25,27]; (7) pesticide costs range from € 3.37 to € 13.28 per litre for *Roundup*, based on the same assumptions as mentioned for fertiliser costs, data are from [68,69 and G.V. Roman (University of Agronomic Sciences and veterinary Medicine in Bucharest, personal communication 2004)]; (8) labour costs range from € 2.52/h for V2 scenario (current wages in Poland) to € 12.22/h for V3 scenario (average EU level) and € 14.63 for V1 and V4 scenario (increase compared to average EU level because of strong economy and more efficient production system), data are from [27,29]; (9) Machinery and labour input for harvesting are based on data from [27,66,70] and differentiated per scenario based on yield levels and costs for wages and machinery. Input data range for machinery from 3.75 €/t_{dm} per rotation for V2 to 11.06 €/t_{dm} per rotation for the V1 and V4 scenarios); (10) Insurance and miscellaneous costs are based for the V3 scenario on data from [27], assuming a 10% increase for the V1 and V4 scenarios and a 5% decrease for the V2 scenario.

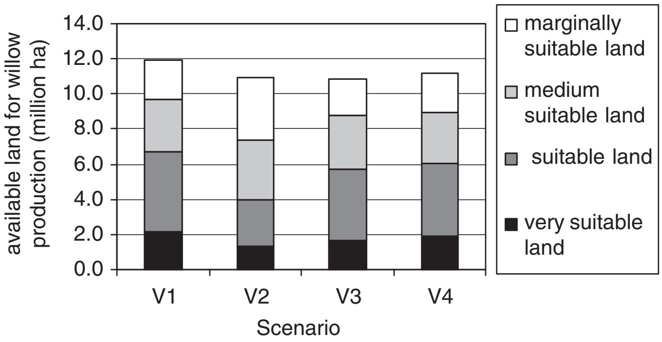

Fig. 4. Projected available agricultural land in 2015 for the production of biomass (i.e. short rotation wood) after subtracting land for food demands.

Analysing land markets, new rents of agricultural land were determined. Input data for these calculations are the basic land rents, the total amount of agricultural land (see Table 3) and the elasticity of agricultural land. No estimates for own-price elasticity of land could be identified from literature. Rather, own-price elasticity of food is used for the whole agricultural sector [31]. This is due to the fact that the demand for agricultural land is closely related to the demand for food. Estimates for the own-price elasticity of food vary considerably.[11] Ciaian et al. [31] estimate elasticities of −0.18, −0.24 and −0.3 for the Czech Republic, Poland and Slovakia, respectively. The medium value of −0.24 was used as an estimate for Central Eastern Europe in the V2 scenario. In the V4 scenario, a slightly higher value of about −0.2 was assumed as presented for the Netherlands by van Driel et al. [19] to be applicable for the EU-25. Finally, no global estimate for the elasticity of food demand could be identified. As in the global V1 scenario current US land rents are assumed, an elasticity factor for food demand in the US of −0.45 [19] in the global land markets of the V1 and V3 scenarios was assumed.

3.2. Biomass applications and their markets

In this section, input data on the four biomaterial and bioenergy systems i.e. MDF, PLA, methanol and electricity production are described. Key parameters for the characterisation of biomass applications are the input of short rotation wood, the production costs and the GHG emission reduction in relation to the reference system; see Table 4. Furthermore, MDF, PLA and their reference materials, i.e. plywood and PE, are converted to electricity after their use. The resulting electricity is assumed to replace electricity from the grid and, thus, to contribute to GHG emission reduction and revenues from sales.

Data on material and energy markets are summarised in Table 5. These are market volumes, market prices, Polish market shares and own-price elasticities of the biomass applications based on statistics. While the growth of GDP may change the demand of materials and energy carriers in 2015, in this study no changes of material and energy demands were assumed, but current market volumes were used. First, this is because the demand for materials and energy carriers does not develop one by one with the growth of GDP since energy efficiencies increase and sectoral changes may occur that influence material and energy intensities; see [33]. Second, keeping market volumes of materials and energy carriers constant, enables us to investigate market effects on GHG emission mitigation costs without disturbing influences. In the sensitivity analysis, however, the influence of this assumption was evaluated, see Section 4.5.

In general, GHG emissions were calculated with carbon emission factors representing indirect and direct GHG emissions of average European energy use in 2000.[12] For fuel, the average EU oil product mix for production (83 kg CO_{2eq}/GJ) and for electricity, the average EU mix of electricity production (126 kg CO_{2eq}/GJ) were used [34]. The GHG emissions of biomass production are derived from production inputs of short rotation willow production in Poland [35] and generic GHG emissions of machine uses, fertilisers, etc. mainly from [36]. The resulting GHG emissions are about 0.23 kg CO_{2eq}/ha; see [3] for a more detailed description of GHG emissions from biomass production.[13]

3.2.1. MDF

The input of wood for MDF is based on a study of hardboard which has a comparable production process [38]. Concerning GHG emission reduction, it is assumed that MDF replaces plywood with the volume of board as functional unit.[14] The GHG emission reduction was then calculated from the GHG emissions during plywood and MDF production[15] [28,39–41]. Also, GHG emissions that could be saved if forestry wood for plywood production

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[11] Finke et al. [32] estimate elasticity factors between −0.03 and 0.64. For the US, they estimate an elasticity of −0.03, while Driel et al. [19] determine this elasticity to be −0.45.

[12] GHG emission factors of energy use vary within geographical regions and are likely to change in the future. Future specific GHG emissions depend on economic developments and governmental policies and are, therefore, scenario specific; see e.g. [16]. In this analysis, GHG emission factors of energy use were kept constant in order to investigate market effects on GHG emission mitigation costs without disturbing influences of varying GHG emission factors.

[13] Different biomass production systems for Poland, i.e. 'current input', 'high input' and 'high advanced input' are assumed in the scenarios. These production systems use different levels of inputs per hectare, e.g. machinery and fertilisers, but also lead to different levels of short rotation willow yields per hectare. Because of a lack of data on GHG emissions of the various production systems, it is assumed that GHG emission per unit of biomass produced is constant. This assumption can be justified by findings for miscanthus for which the share of energy input (including drying) at the end use energy varies only about 8–14% for different production systems [37].

[14] This is equivalent to 1 kg of MDF board replacing about 0.71 kg of plywood [39].

[15] Data on MDF board and plywood production take into account that processing residues are used for process heat generation.

Table 4
Input data of biomass options for the use of SR wood to reduce carbon emissions

	MDF	PLA		Methanol	Electricity	
SR wood input (dm)	1.3	0.68	kg_{wood} /kg	0.10	0.13	kg_{wood}/GJ
GHG em. reduction	0.82	3.97	kg CO_2 eq/kg	42.6	94.2	kg CO_{2eq}/GJ
Production costs[a]	250	1210	€/kg	6.2	14.6	€/GJ
Electricity recovery[b]	1.62	−7.65	GJ_e/kg	—	—	

[a] Production costs are without costs of biomass inputs, because biomass costs vary within the different scenarios.

[b] In the V1 and V4 scenarios, electric efficiency of waste incineration is 30% (LHV), which is State-of-the-Art in Europe. Lower heating values are 15 GJ/Mg for MDF, 13.5 GJ/Mg for plywood, 43.4 GJ/Mg for HDPE and 17.9 GJ/Mg for PLA.

Table 5
Input data of biomaterial and bioenergy markets

	MDF	PLA	Methanol	Electricity
Market volume				
V1	15.2 million Mg (World)	All scenarios:	All scenarios:	8.9 EJ (World)
V2	1.0 million Mg (CEE)	0.14 million Mg (World)	58.8 EJ (World)	1.3 EJ (CEE)
V3	15.2 million Mg (World)			8.9 EJ (World)
V4	5.2 million Mg (EU-25)			8.9 EJ (World)
Market price				
V1	279 €/Mg	All scenarios:	All scenarios:	19.4 €/GJ
V2	453 €/Mg	3000 €/Mg	8.9 €/GJ	13.8 €/GJ
V3	279 €/Mg			19.4 €/GJ
V4	366 €/Mg			19.4 €/GJ
Market share Poland				
V1	5%	All scenarios:	All scenarios:	4%
V2	85%	0.3%	0.5%	27%
V3	6%			4%
V4	16%			4%
Own-price elasticity				
V1	−1.11	All scenarios:	All scenarios:	All scenarios:
V2	−1.79	−0.55	−0.23	−0.15
V3	−1.11			
V4	−0.95			

would be used for electricity production are added to the GHG emission reductions. Production costs of MDF were estimated to be the difference between the prices of the raw material, i.e. wood chips, and the export prices of MDF board in Europe derived from statistics on wood products trade [20]. Data on the production and GHG emission reduction of MDF as summarised in Table 4 have already been discussed in a study of short rotation wood cascading; see [4].

The market volume, i.e. the consumption of MDF boards, is currently (in 2002) about 23.3 million m^3 in the world, 8.0 million m^3 in Europe and 1.5 million m^3 in Central Eastern Europe [20]. Market volumes in Table 3 are converted to Mg with an average density of MDF board of 0.65 Mg/m^3 [39]. Polish market shares of MDF board production in comparison to MDF board consumption have been 5.3% globally, 15.6% in whole Europe and 84.6% in Central Eastern Europe [20]. Market prices are based on the import prices for fibreboard in the world, Europe and Central Eastern Europe, respectively, in 2002 [20].[16] The own-price elasticity of MDF board demand was estimated by regression analysis from historical import prices and consumption values; see Fig. 5. These data are available for 1995–2002 [20].

3.2.2. PLA

The efficiency of PLA production is based on current ligno-cellulose pre-treatment [42,43] and current estimations about PLA production from ligno-cellulose [44]. It was assumed that 1 kg of PLA replaces 1 kg of HDPE. GHG emissions are the emissions of PLA production caused by energy uses [44] but accounting for the fact that lignin from short rotation wood is used for process heat and electricity production. Subsequently, net emissions were determined by subtracting GHG emissions of HDPE

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[16] Exchange rate used for conversion to € is the average rate in 2002 of 1.06 US$/€.

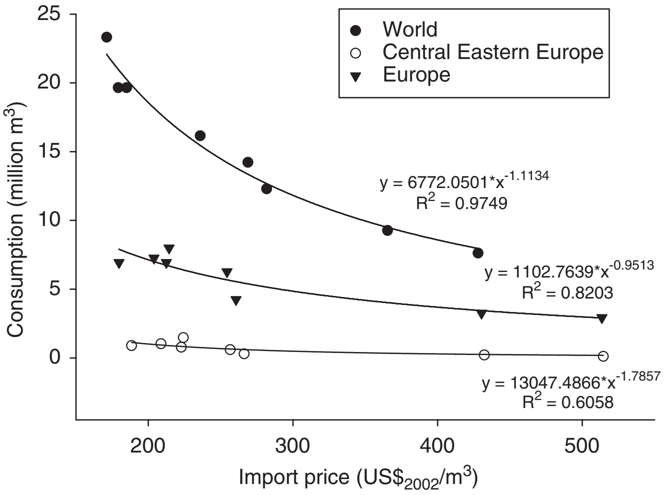

Fig. 5. Historical data on demand and prices of MDF board used for the estimation of own-price elasticity; data from FAO (2004).

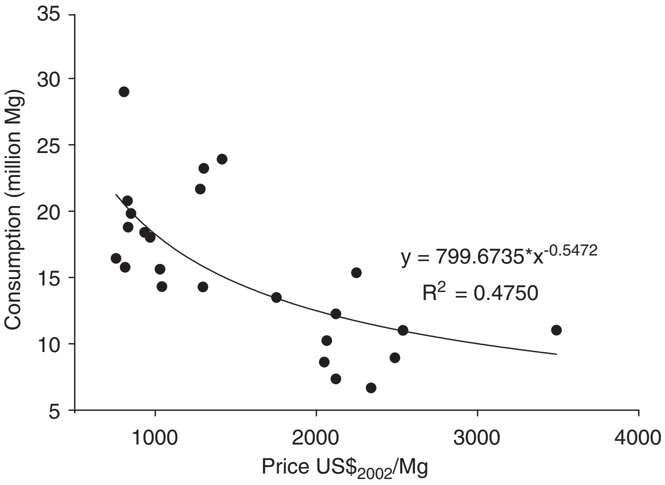

Fig. 6. Historical data on global demand and prices of polyethylene used for the estimation of own-price elasticity; data from UN (2000) and Crank et al. (2005).

production [45]. Production costs of PLA were taken from projections of Cargill Dow planning to produce PLA from corn stover [46]. Because HDPE has a much higher heating value than PLA, the net electricity recovery from waste is negative for PLA production. All analyses on energy and GHG balances of PLA production are reported in a study of a PLA bio-refinery; see [6].

The global market volume of PLA is the current global production of PLA in 2003 of about 0.14 million Mg [46]. Current global market prices are taken from a study on bio-based polymers [46]. At the moment no PLA is produced in Poland. Therefore, we use Polish market shares of polyethylene production as fictious market shares of PLA production [47]. Because the production of PLA (and other bio-based polymers) is a rather new development, no historical data on market prices and production volumes are available. As PLA has the potential to substitute PE on a large scale, the own-price elasticity of PE was used in this analysis. It was estimated from historical figures of global PE production and market prices by regression; see Fig. 6 [46,47].

3.2.3. Methanol

Data on methanol production refers to an advanced methanol production concept without electricity co-production and a conversion efficiency of 57% (HHV) as investigated by Hamelinck and Faaij [48]. Production costs include distribution costs in order to make the production costs comparable to the market prices for end-users used in this analysis.[17] To determine GHG emission reduction, it was assumed that $1\,\mathrm{GJ_{LHV}}$ methanol replaces $1\,\mathrm{GJ_{LHV}}$ gasoline.

Methanol was assumed to be sold for market prices of gasoline in advanced economies without taxes.[18] The market volume for methanol is the global consumption of petroleum products for road transport, i.e. 58.8 EJ in 2000 [51]. In 1999, the Polish gasoline production was about 0.3 EJ [47].

Espey [52] compared more than 300 estimates of short-run own-price elasticity of gasoline demand, i.e. describing the relation between prices and demand in the short to medium term. These estimates are derived from economic models as well as time-series analysis. The median of all estimates is −0.23 and was used in this analysis.[19]

3.2.4. Electricity

The data for electricity production are based on a state-of-the-art IG/CC plant (about 150 $\mathrm{MW_e}$) with a net electric efficiency (LHV) of 43.5% [53]. Also for electricity, distribution costs are added to the production costs as market prices used are for end-users.[20] It was assumed that electricity from short rotation wood replaces electricity from the European grid on a kWh basis.

The market volumes of electricity are the consumption of electricity in the year 2000, in the EU-25 and Central Eastern Europe, respectively [55,56]. Market prices for

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[17] The methanol production technology considered is currently under development and is likely to be commercial in 2015–2020. The selected concept uses an atmospheric indirectly fired gasifier, wet gas cleaning, steam reforming and liquid phase methanol production [48]. Production costs are based on an interest rate of 5%, a scale of 400 MWth, a base load of 8000 h/yr, an economical lifetime of 15 years and a technical lifetime of 25 years. Assuming biomass costs of 2 US\$/$\mathrm{GJ_{HHV}}$, methanol production costs of 7.2 US\$/$\mathrm{GJ_{HHV}}$ result [48]. Distribution costs are about 2.1€/$\mathrm{GJ_{HHV}}$. [49]

[18] Market prices were averaged from prices in USA, Canada, Japan, France, Germany, Spain, Italy and the UK in 2003–2004 [50].

[19] Estimates of the short-term elasticity range from 0 to −1.36 [52].

[20] The lower heating value of short rotation wood was assumed to be 17 GJ/Mg. Production costs of electricity are calculated from the investment costs of the IG/CC plant of 1.97 million €/$\mathrm{MW_e}$ [53], a lifetime of 25 years, an interest rate of 5% rent and a load factor of 80%. In Western Europe, i.e. in DK, D, F, the Netherlands, UK distribution costs for large-scale consumers are about 0.01–0.02 €/kWh [54]. In this study, distribution costs of 1.5 cent/kWh (4.2 €/GJ) were assumed.

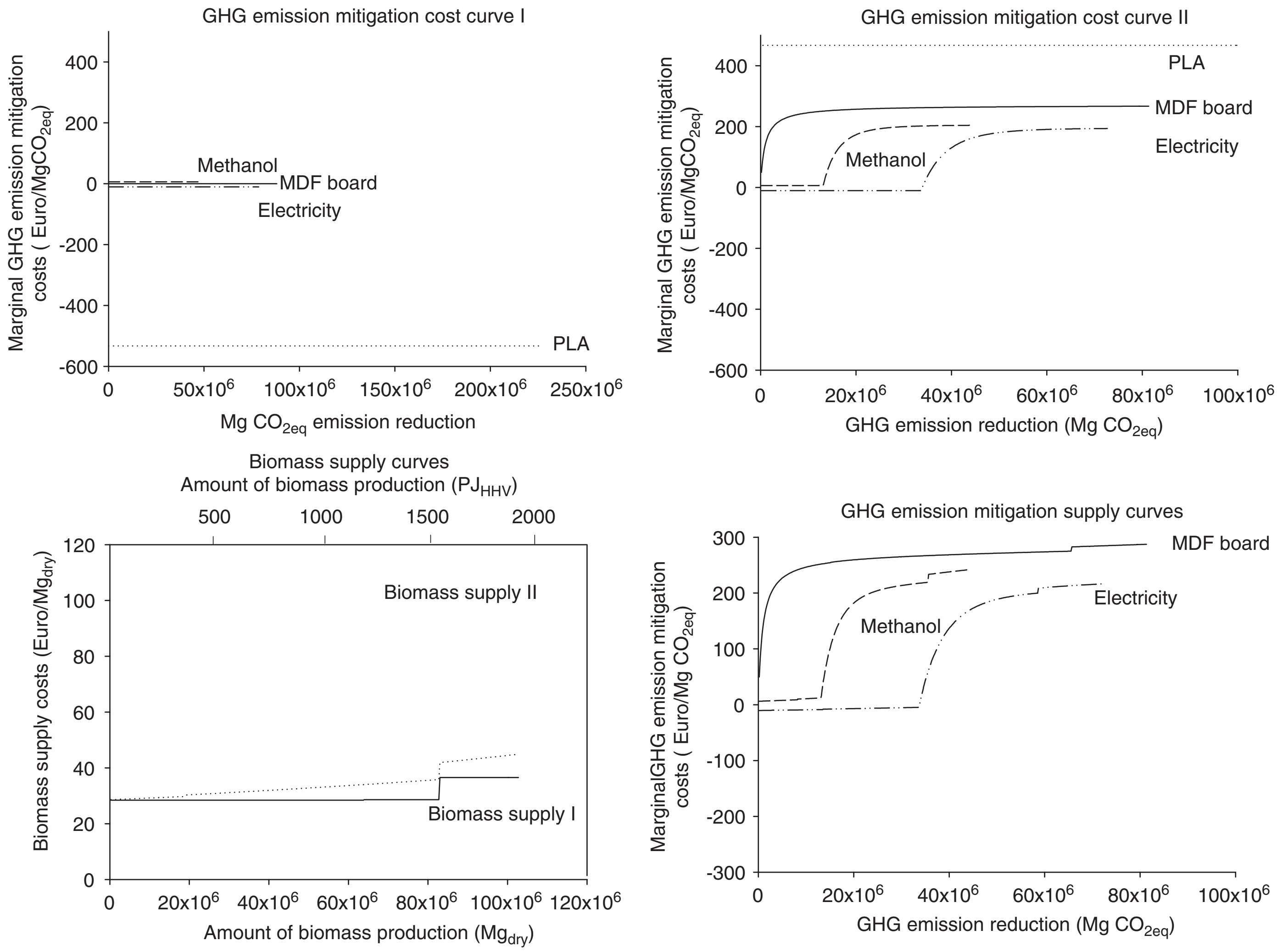

Fig. 7. GHG emission mitigation cost curves, biomass supply curves and overall supply curves for GHG emission mitigation in scenario V1.

electricity vary between consumers and countries.[21] In this analysis, about average market prices without taxes that apply to large-scale household and medium industrial-scale users were used. In the EU-25 these are about 0.07 €/kWh and in Central Eastern Europe about 0.05 €/kWh [57,58]. Polish electricity consumption in the year 2000 was about 0.35 EJ_e [55].

Own-price elasticity estimates in economic literature are usually given for limited markets but not for whole regions as the EU-25 or global. Estimates for elasticity of electricity in scientific literature, however, are in a comparable range. Kamerschen and Porter [59] estimated the elasticity of total electricity demand in the US between −0.13 and −0.15 and found that this value is within the same range as other US-based studies. Wolfram [60] analysed the British spot market, concluding that the data suggest a price elasticity of approximately −0.1. SEO [61] investigated industrial electricity use in the Netherlands resulting in an own-price elasticity of −0.2. Given this information, own-price elasticity of electricity is not differentiated between the scenarios, but a value of −0.15 is assumed.

4. Results

All steps of the calculation, i.e. the biomass supply curves I + II, the GHG emission mitigation costs curves I + II and the resulting GHG emission mitigation supply curves for PLA, MDF, methanol and electricity are shown for each scenario in Figs. 7–10.

4.1. Biomass supply curves

The biomass supply curves I show biomass production costs in Poland. In the V1 scenario, a large amount of biomass of about 88 million Mg_{dry} is available at relatively low prices below 36 €/Mg_{dry}[22] Production costs, e.g. labour

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[21] For example, in the EU-25 market prices without taxes vary from 0.035 €/kWh for large-scale industrial users in Latvia and 0.350 €/kWh for small-scale household users in Norway [57,58].

[22] 1 Mg_{dry} of biomass, i.e. short rotation willow, has a higher heating value of about 18.4 GJ/Mg. Biomass costs of about 2 €/GJ_{HHV} are, therefore, equivalent to about 36.8 €/Mg_{dry}.

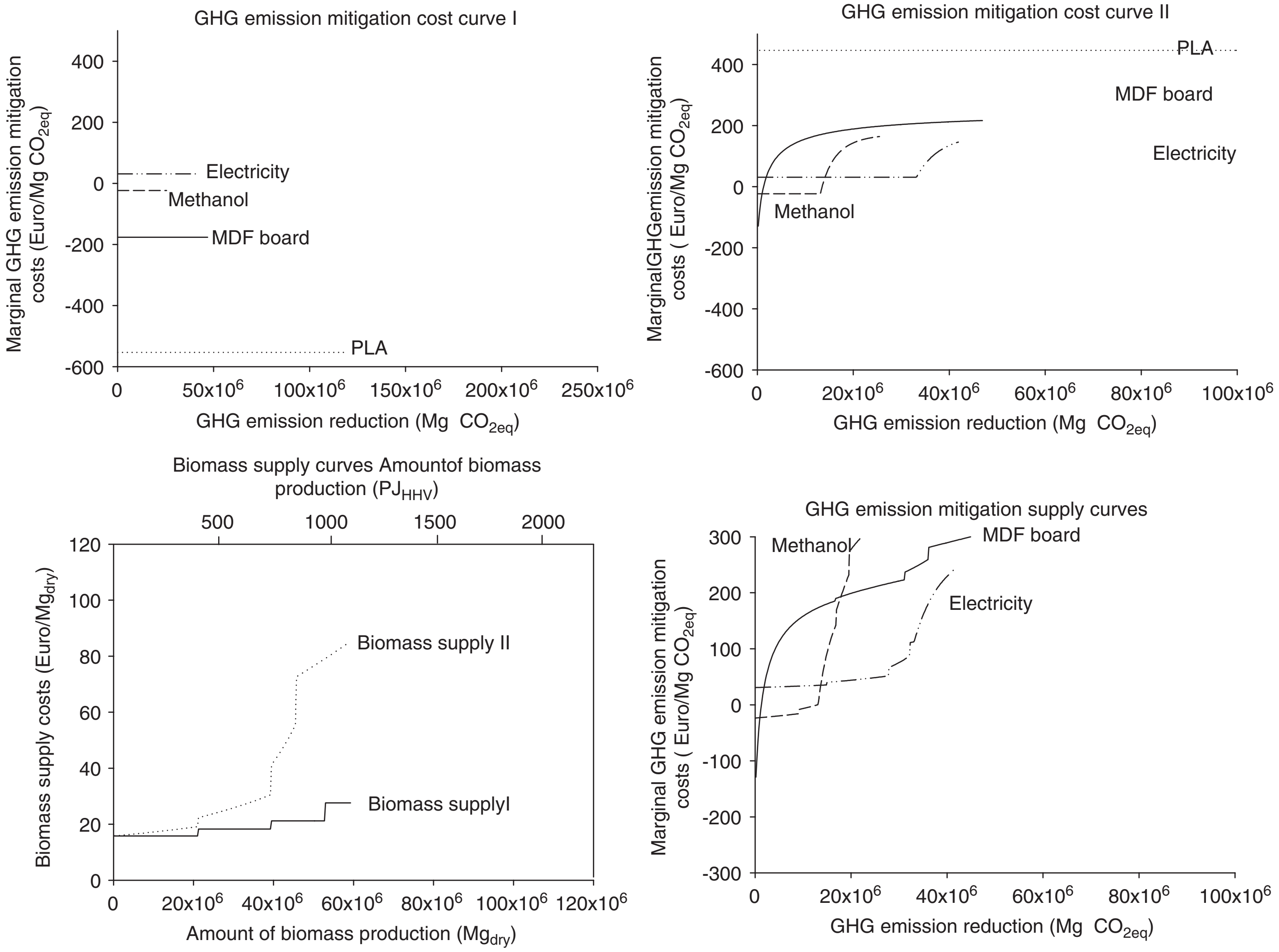

Fig. 8. GHG emission mitigation cost curves, biomass supply curves and overall supply curves for GHG emission mitigation in scenario V2.

and land, are even cheaper in the V2 scenario in which economic development of Eastern Europe stagnates. However, as yields are also lower and food production is in principle self-sufficient, about 59 million Mg_{dry} of biomass are available at costs below 28 €/Mg_{dry}. In the V3 scenario biomass production is quite expensive as levels of input, i.e. machinery, labour, fertilisers, etc., and their costs per unit are high. Thus, only 21 million Mg_{dry} of biomass can be produced at lowest possible costs of about 51 €/Mg_{dry}. The V4 scenario is characterised by even higher production costs and high average land rents. As a consequence, the lowest biomass production costs are 60 €/Mg_{dry} for which about 28 million Mg_{dry} of biomass are available.

The biomass supply curves II also take into account that land rents will increase if biomass for material and energy is produced on a larger scale. Adding the increase of land costs to the biomass supply curves increases the biomass production costs considerably, especially at large scales of biomass production. The higher the basic land rents in a scenario, the higher is the increase of land rents by increasing biomass production. For example, in the V2 scenario with low land rents, the increase of biomass production costs is relatively small, not exceeding 70 €/Mg_{dry} even at large scale.

4.2. GHG emission mitigation cost curves

The GHG emission mitigation cost curves I show that these costs are not considering variable market prices of products and land. Also, biomass supply curves are not taken into account in the calculation of the GHG emission mitigation cost curve I. Thus, the results are indifferent to the volumes of biomass application produced and represent the GHG emission mitigation costs without the possible influences of a large-scale introduction of biomass material and energy production.

The GHG emission mitigation cost curves I are depicted up to the amount of available biomass given in the biomass supply curves. PLA production has the technical potential to avoid by far the largest amount of GHG emissions using the available biomass. In decreasing order, MDF production,

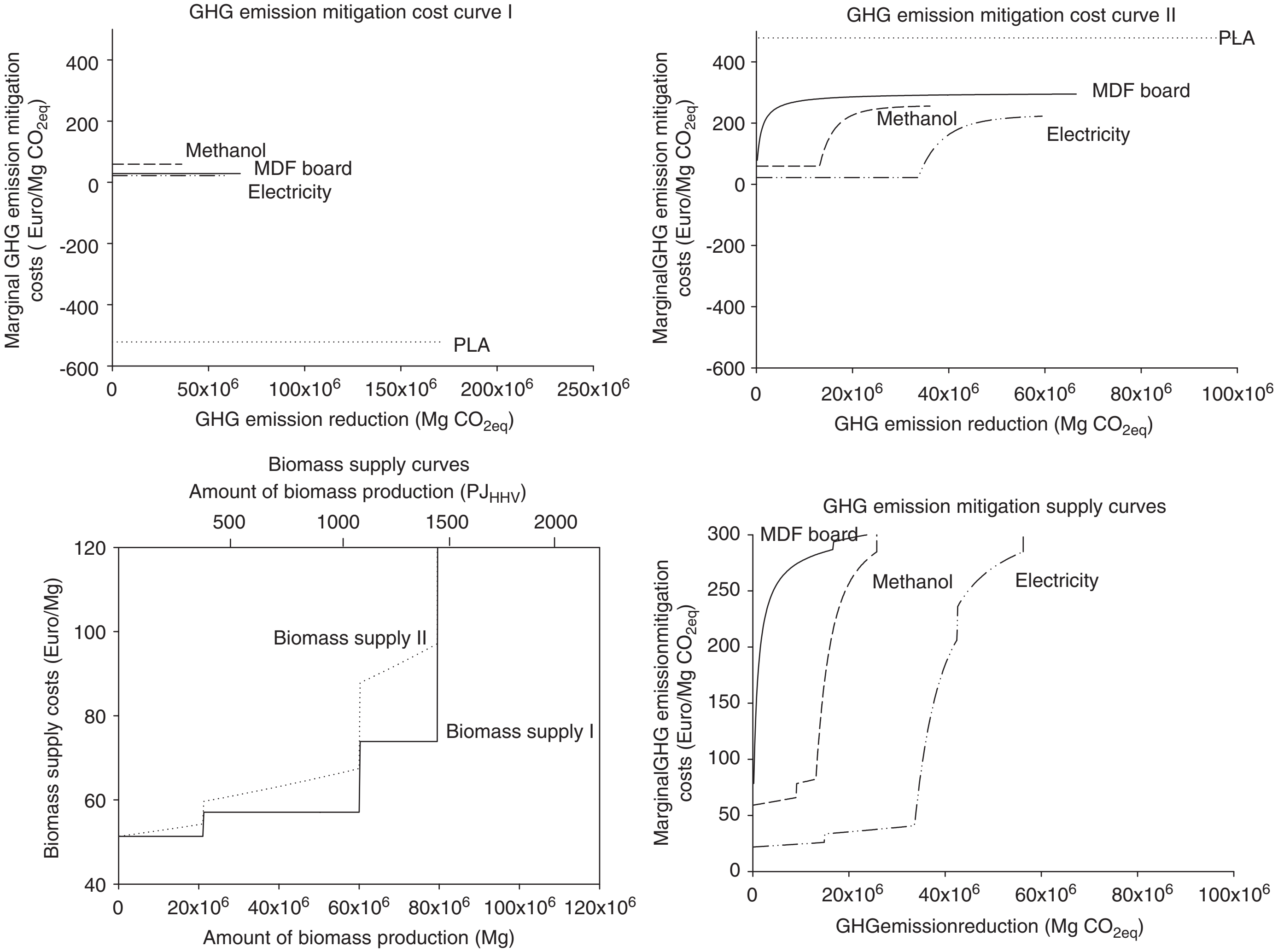

Fig. 9. GHG emission mitigation cost curves, biomass supply curves and overall supply curves for GHG emission mitigation in scenario V3.

electricity production and methanol production have lower technical potentials to avoid GHG emissions.

PLA production at current market prices results in all scenarios in low GHG emission mitigation costs of about −500 €/Mg CO_{2eq}. In the V2 scenario, high market prices of MDF in a Central Eastern European market were assumed. These assumptions result in GHG emission mitigation costs of about −200 €/Mg CO_{2eq} for MDF production[23] In the V4 scenario, biomass production costs are assumed to be relatively high. As a result GHG emission mitigation costs of electricity production are with 100 €/Mg CO_{2eq} relatively high, too. The remaining options in the different scenarios have GHG emission mitigation costs of around zero.

The GHG emission mitigation cost curves II show the influence of material and energy markets on these costs by changing biomaterial and bioenergy prices depending on the volume produced. In all scenarios, the GHG emission mitigation costs of PLA production first increase strongly and then stay nearly constant with increasing amounts of GHG emissions avoided. This is due to the relative small market volumes of PLA. With increasing PLA production, market prices of PLA decrease rapidly until the demand curve becomes nearly constant.[24] For MDF board, methanol and electricity, a similar but less pronounced effect can be observed in Figs. 7–10. The smaller the market volumes of the biomaterial or bioenergy carrier are, the larger is the increase of GHG emission mitigation costs with the amount of GHG emissions avoided. For methanol and electricity, however, in the first part of the curves, the GHG emission mitigation costs are constant, because it was assumed that alternative energy carriers are replaced at constant market prices; see Section 2.4. In all scenarios, the amount of GHG emissions that can be avoided without an

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[23] Negative GHG emission mitigation costs result from the fact, that revenues from material and energy sales are higher than production costs of these materials and energy carriers.

[24] This increase is not visible at the scales in Figs. 7–10, but the GHG emission mitigation costs appear to be constant.

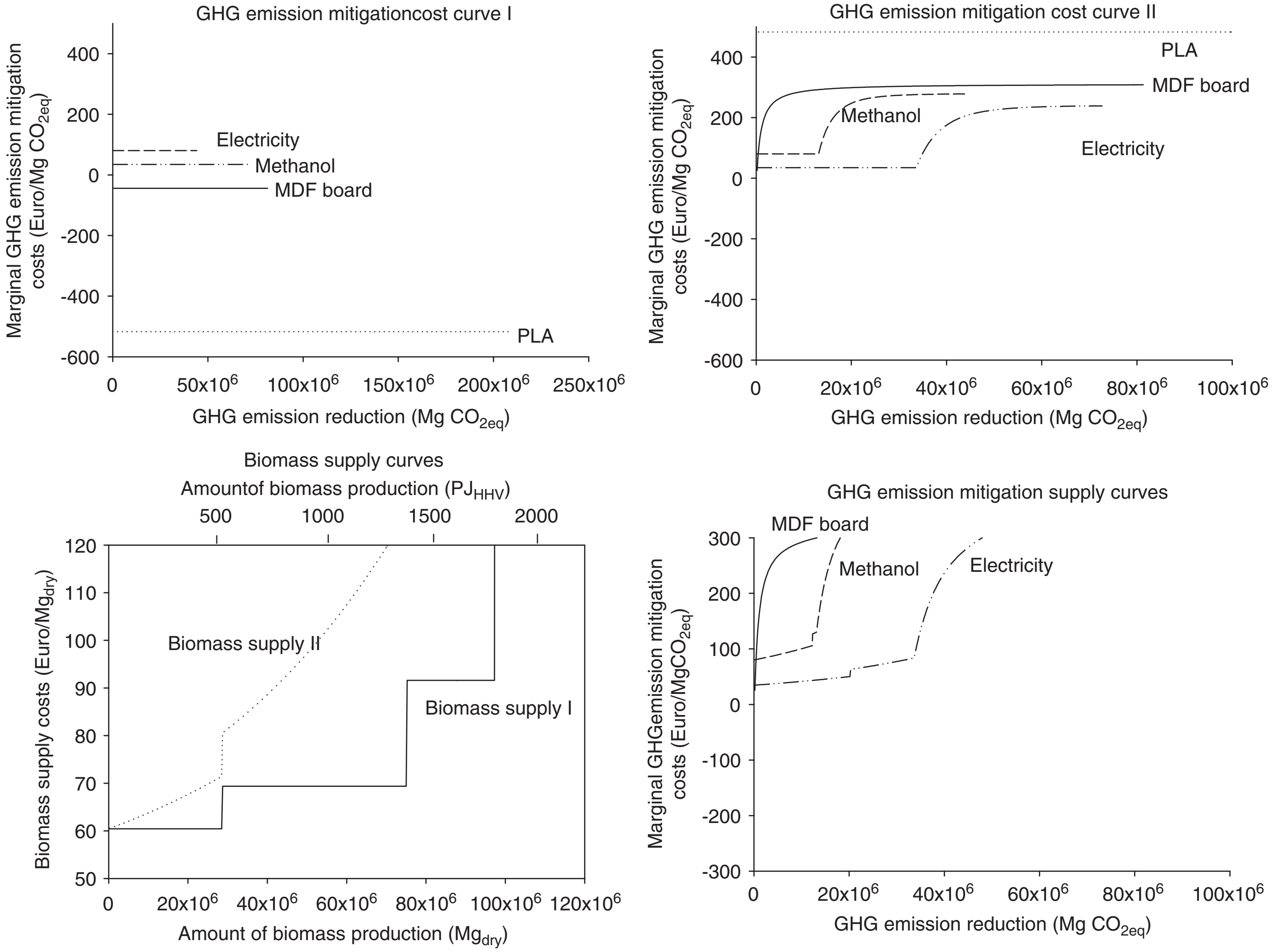

Fig. 10. GHG emission mitigation cost curves, biomass supply curves and overall supply curves for GHG emission mitigation in scenario V4.

increase of GHG emission mitigation costs is larger for electricity than for methanol.

4.3. *GHG emission mitigation supply curves*

In the GHG emission mitigation supply curves, costs of biomass production from the biomass supply curve II are combined with costs of the GHG emission mitigation cost curves II. Only GHG emission mitigation costs curves up to 300 €/Mg CO_{2eq} are depicted, as measures with higher costs are very unrealistic to be implemented.[25] Because MDF, PLA, methanol and electricity production technologies use different amounts of biomass per unit of GHG emission reduction, the influence of the biomass production costs on these options varies.

4.4. *Comparison of scenarios*

Fig. 11 shows the 'integral' GHG emission mitigation cost supply curves for the different scenarios, i.e. for each amount of biomass used, the cheapest biomass material or energy option of the technologies considered is applied.

The specific GHG emission reduction, i.e. Mg CO_{2eq} avoided per unit of biomass use, differs only slightly between the technologies used for GHG emission mitigation in the scenarios. Therefore, the shape of the 'integral' GHG emission mitigation supply curves per unit of biomass used (left part of Fig. 11) and per unit of GHG emissions avoided (right part of Fig. 11) hardly differs.

In the V1, V3 and V4 scenarios, electricity production from biomass is preferred in the first instance for GHG emission mitigation as long as electricity prices stay constant. Second, methanol production from biomass is used for the part of the market volume in which methanol prices stay constant. Finally, MDF, electricity and methanol production are applied in the last part of the integral GHG emission mitigation supply curve. The use of

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[25] According to the IPCC, costs of promising GHG emissions reduction options are at present in a range of up to 60 US$/Mg CO_{2eq}. [62] However, at costs of 60 US$/Mg CO_{2eq}, only a small part of the total GHG emission mitigation supply curve would be visible. Therefore, costs of up to 300 €/Mg CO_{2eq} are shown.

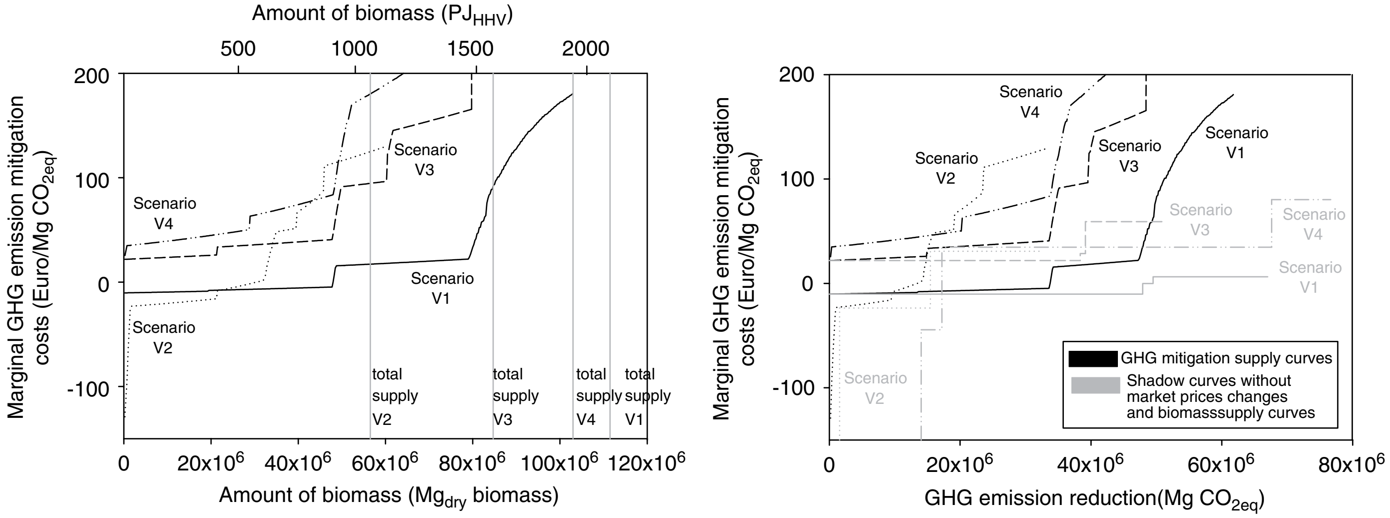

Fig. 11. Comparison of overall GHG emission mitigation supply curves for the different scenarios.

the different technologies alternates. This is due to the fact that with increasing use of one technology its GHG emission mitigation costs increase and, finally, exceed the GHG emission mitigation costs of another technology. In the V2 scenario, first MDF production is applied for a small part of GHG emission mitigation. Second and third, methanol and electricity production are used.

GHG emission mitigation costs in the V1 and V2 scenarios are relatively low. In the V1 scenario about 49 and 34 million Mg CO_{2eq} are avoided for costs below 50 and 0 €/Mg CO_{2eq}, respectively. In the V2 scenario, these amounts are about 18 and 13 million Mg CO_{2eq} avoided. In the V3 and V4 scenarios, however, biomass production costs are relatively high, especially at large scales of production. As a consequence, GHG emission mitigation costs in these scenarios are higher and no GHG emissions are avoided at costs below 0 €/Mg CO_{2eq} and about 34 and 20 million Mg CO_{2eq}, respectively, are avoided at costs below 50 €/Mg CO_{2eq}.

To show the impact of a large-scale introduction of biomass, shadow curves of GHG emission mitigation costs are depicted in the right part of Fig. 11. These curves show the GHG emission mitigation costs in the different scenarios without considering market price changes of materials, energy carriers and increasing costs of biomass supply. The same amount of each technology, i.e. MDF, PLA, methanol or electricity, is used for the shadow curves as in the respective scenarios. The shadow curves show that market mechanisms and increasing biomass supply costs lower the GHG emission reduction potential at low costs considerably. The potential GHG emission reduction at costs below 50 €/Mg CO_{2eq} decreases from 67 to 49 million Mg CO_{2eq} in the V1 scenario, from 33 to 18 million Mg CO_{2eq} in the V2 scenario, from 39 to 34 million Mg CO_{2eq} in the V3 scenario and from 68 to 20 million Mg CO_{2eq} in the V4 scenario.

Poland is a country with large biomass production potential. While the total primary energy consumption of Poland in 2000 is about 3.8 EJ [55], the total biomass supply (short rotation wood) in the different scenarios varies between 1.1 and 2.0 EJ.[26] However, at relatively low GHG emission mitigation costs of below 50 €/Mg CO_{2eq} only about a half to two third of this biomass can be used with the options considered in this study. As biomaterials have only a small potential of GHG emission mitigation at low cost, the production of other bioenergy carriers, e.g. heat, would be necessary to use a larger part of this biomass potential.

4.5. *Sensitivity analysis*

The influences of assumptions about the material and energy market on the integral GHG emission mitigation costs supply curves were analysed in a sensitivity analysis. Also, many other factors influence the final GHG emission mitigation supply costs, e.g. biomass production costs, efficiency of material production, the reference system and market prices. In this study, however, our main interest is the possible change of GHG emission mitigation costs through the variability of market prices if biomass material and/or energy uses are introduced on a large scale. Therefore, only the main factors influencing these markets, i.e. elasticity, the total market volume and the Polish market shares, were investigated here. An overview of the variation of parameters in the sensitivity analysis is given in Table 6. For illustration, this sensitivity analysis was carried out for the V1 scenario which has the largest GHG emission mitigation potential at low costs.

As discussed in Section 3, values of elasticity for the different markets are quite uncertain and various estimates exist. These often-broad ranges are used for the sensitivity analysis. For land markets the range of elasticities presented in [32] was assumed. For all kind of biomaterials,

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[26] In these potentials agricultural and forestry residues are not included, which amount to about 0.2–0.6 EJ.

Table 6
Variation of elasticity factors and market volumes in the sensitivity analysis of scenario V1

	Land	MDF board	PLA	Methanol	Electricity
Base elasticity	−0.45	−1.11	−0.55	−0.23	−0.15
Range elasticity	−0.03 to −0.64	−0.5 to −1.8	−0.5 to −2.5	−0.05 to −1.36	−0.1 to −0.2
Base market volume	N/a	15.2×10^6 Mg	0.14×10^6 Mg	58.7 EJ	45.6 EJ
Range market volume	N/a	±10% of volume	±10% of volume	±10% of volume	±10% of volume
Range market share	N/a	+100/−50% of share	+100/−50% of share	+100/−50% of share	+100/−50% of share

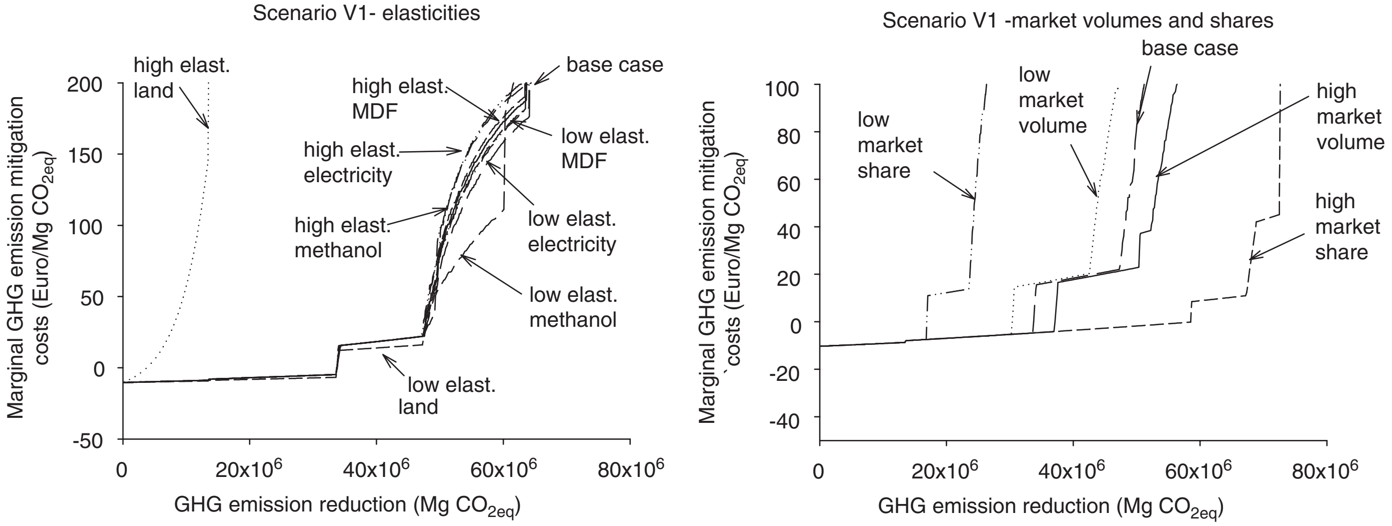

Fig. 12. Variation of integral GHG emission mitigation cost supply curves (of scenario V1) due to the variation of elasticity factors and market volumes.

Gielen et al. [63] estimate own-price elasticity to be −0.5. This value was used as higher range for MDF and PLA. The lower range of elasticity for MDF is the lowest value derived from historical data. The lower value for PLA was from price and volume forecast from producers in Crank et al. [46]; see also [6]. For methanol, the range of elasticity found in the meta-analysis of [52] was used.[27] Finally, for electricity the values estimated by Wolfram [60] and SEO [61] were used as ranges.

Market volumes of materials and energy carriers in this analysis may vary because the total demand changes without related market price changes, e.g. by income variations. Also the market share of Poland on the respective market may increase or decrease depending strongly on the competitiveness of Polish production. To account for these possible changes, a variation of market volumes of 10% and a variation of market shares from half to twice the value is considered for the sensitivity analysis.

In Fig. 12, the influence of the variation of elasticities (left part of Fig. 12), market volumes and market shares (right part of Fig. 12) on the integral GHG emission mitigation costs in scenario V1 is presented. The sensitivity analysis shows that the own-price elasticity of land demand has a strong influence on the GHG emission mitigation costs. If this elasticity is in the upper range, GHG emission mitigation costs increase rapidly reducing the potential of GHG emissions that can be avoided at costs below 50 €/Mg CO_{2eq} by 80%. The influence of other elasticity factors on the integral GHG emission mitigation costs is limited to the part of the curve in which market prices are not constant. With low own-price elasticities, the increase of GHG emission mitigation costs with increasing scale of biomass use is slightly less than in the base case. The opposite applies to high own-price elasticities. At GHG emission mitigation costs of about 100 €/Mg CO_{2eq}, GHG emission potentials vary about 0.01–10% through the variation of own-price elasticities of materials and energy carriers. The variation of market volumes and market shares has a large influence on the integral GHG emission mitigation costs. A higher market volume or share increases the amount of GHG emissions that can be reduced without a decrease of market prices of bioenergy carrier significantly, while a lower market volume decreases this amount of GHG emissions. If the Polish market share is doubled, the potential GHG emission reduction at costs below 50 €/Mg CO_{2eq} also doubles.

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[27] The lowest value of gasoline elasticity is zero. [52] However, we used a value of −0.05 close to zero that allows for calculation with the elasticity function.

5. Discussion

The method used in this article is suitable to highlight the possible influences of large-scale introduction of biomass material and energy systems on market prices of materials and energy carriers and their feedback to GHG emission reduction costs. To determine GHG emission reduction costs for various scenarios, input data on technology performance and biomass production play a crucial role. The data used in this study give an estimation of possible costs. Even though technology development until 2015 will be limited and the possible differences in the developments of biomass production systems have been included in the scenario analysis, uncertainties in these input data may remain. For example, CO_2 intensities of electricity generation may change in the medium-term future due to e.g. the increased use of renewable energies and the replacement of less efficient fossil energy uses. These uncertainties, however, have not been explored in this analysis.

Instead, the analysis concentrates on the influence of market volumes, market shares and own-price elasticity of demand on the GHG emission mitigation costs. The sensitivity analysis shows that own-price elasticities of agricultural land demand and market volumes of bioenergy carriers influence the GHG emission mitigation costs of biomaterial and bioenergy utilisation strongly.

However, not all uncertainties in the developments of markets could be addressed. Elasticity factors for land, materials and energy carriers show a very broad range in the literature. Moreover, own-price elasticity for MDF and PLA had to be estimated by a simple regression analysis. The influence of other factors than own-price elasticity on demand and market prices—e.g. developments in markets of substituting goods—could not be identified in this regression analysis. For this purpose, an econometric analysis would be necessary, which is beyond the scope of the study. For PLA, the results for PLA production may be pessimistic as the market is still developing and may grow.

For market volumes and Polish market shares of bioenergy carriers it has been assumed that the current volume of alternative energy carriers can be substituted. This substitution depends on the competitiveness of bioenergy production with other energy carriers and on the competitiveness of Polish bioenergy production with the production in other countries. This competitiveness may be evaluated by establishing supply curves for energy production. Such an analysis, however, is beyond the scope of this study.

While in principle the effects of increased biomaterial and bioenergy production on their market prices have been included in the approach, other interactions between the large-scale introduction of biomass systems and GHG emission mitigation costs have not been included. For example, with increasing agricultural land prices, food prices increase as well, which may lead to a loss of welfare. Also, it has been assumed that biomaterials and bioenergy carriers substitute reference materials and energy carriers without accounting for any net effects of consumer or producer surpluses.

It may also be possible that the production of reference materials and energy carriers do not equally decrease with the production of biomass applications. Moreover, reference systems may change at large scales of biomass utilisation. For instance PLA may substitute poly(ethylene) first, and if this substitution potential is used, PLA may substitute paper packaging. As a result, the amount of GHG emissions reduced by biomass utilisation changes. Finally, the substitution of different amounts and kinds of reference materials and energy carrier may influence the shape of demand curves for biomass applications. To include these types of interaction a more detailed top-down model would be necessary, which is beyond the scope and objective of this study.

Also the time dimension of the large-scale introduction of biomass use has not been included in our study. The results depict the GHG emission mitigation costs in relation to the scale of biomass production at a certain fictious moment in time, i.e. the year 2015. To implement biomass systems on a large scale, however, will take a certain time span. During this implementation period, technological learning is likely to take place, lowering the resulting GHG emission mitigation costs. These effects have not been considered, because the main objective of this study was to analyse GHG emission mitigation cost changes due to a large-scale utilisation of biomass in a country rather than technological development during implementation strategies. Moreover, the time until 2015 is a rather short period for substantial learning to take place.

6. Conclusions

This study evaluates the possible influences of a large-scale introduction of biomass material and energy systems and their market volumes on market prices of land, materials and energy carriers and subsequently on GHG emission reduction costs. In first instance, it can be concluded that on a country level GHG emission mitigation costs from biomass may increase considerably with the scale of biomass production and utilisation. The potential for GHG emission mitigation below costs of 50 €/Mg CO_{2eq} for the four biomass applications considered is 49 million Mg CO_{2eq} in the V1 scenario (related to SRES scenario family A1), 18 million Mg CO_{2eq} in the V2 scenario (related to SRES scenario family A2), 34 million Mg CO_{2eq} in the V3 scenario (related to SRES scenario family B1) and 20 million Mg CO_{2eq} in the V4 scenario (related to SRES scenario family B2). Without the influence of a large-scale introduction on biomass supply costs and market prices of land, materials and energy carriers, the GHG emission reduction potential at costs below 50 €/Mg CO_{2eq} would be about 13–70% higher, depending on the scenario.

The increase of GHG mitigation costs depends on biomass supply curves, the increase of agricultural land costs and the decrease of market prices of material and energy carriers. Biomass supply costs increase between 20 and 100 €/Mg_{dry} in the different scenarios, if all land that is not necessary for food production is used for biomass production. Additionally, the increase of agricultural land rents due to increased biomass production adds up to 50–100 €/Mg_{dry} to biomass production costs at large scales. At large scales of biomass use that exceed the volumes of current markets for energy carriers, GHG emission mitigation costs increase rapidly due to changes of market prices of material and energy carriers. At these scales, GHG emission mitigation cost levels rise to very high values.

Biomaterial production covers only a small part of GHG emission mitigation at low costs. This is due to relative small material markets and the subsequent strong decrease of market prices of biomaterials at large scale of production. Instead, bioenergy production is mainly applied for GHG emission mitigation as energy markets are comparably large and alternative energy carriers can be substituted at a large scale without decreasing market prices. Therefore, both supply and demand of materials and especially energy carriers should be analysed jointly to quantify the amounts that realistically can be used in a country/region.

GHG emission mitigation costs depend strongly on own-price elasticity of land and market volumes of bioenergy carriers. To a lesser degree, GHG emission mitigation costs also depend on the own-price elasticity of materials and energy carriers and market volumes of biomaterials. However, literature estimates of own-price elasticities are highly uncertain and market volumes of biomass applications depend on their competitiveness.

This analysis shows the importance of considering both biomass supplies and potential demands and markets simultaneously to get a more realistic picture of optimal biomass utilisation strategies for GHG emission mitigation. Hence, it would be ideal to combine the bottom-up approach demonstrated here with an analysis of market effects using top-down modelling.

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