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Abstract

Biorefineries, especially if based on woody biomass, may cause significant changes to the forest and wood-based industry. The resulting changes may, in turn, affect the economic feasibility of lignocellulosic biofuels production. In this article, we introduce a spatial partial equilibrium model of the forest and wood processing industries in Germany. The wood market model is linked to the Reaction Network Flux Analysis (RNFA), a model for the systematic selection of reaction pathways in the preliminary evaluation of the mass balance of innovative biofuel components. In doing so, we can simulate the impact of wood-based biorefineries on their feedstock markets and also assess the economic feasibility of the proposed production process. In a case study based on the transformation of beech wood to methyltetrahydrofuran (MTHF), a potential biofuel component currently under development, we show how the net present value of lignocellulosic biorefineries of various sizes is completely reversed once the wood market's response to the entry of a new high-volume consumer is taken into account.

Keywords: Biorefinery, process design, spatial partial equilibrium model, German wood market.

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1 Introduction

Recently, renewable raw materials are attaining great interest in the production of chemicals and fuels. A change in raw materials feedstock should be considered an opportunity to fundamentally adjust the industrial value chains. However, several difficulties must be faced before biomass will constitute a competitive feedstock (Marquardt et al., 2010). Desirable product characteristics (e.g. the combustion properties of biofuels) will significantly influence the bio-chemical production procedure, whereas the cost and availability of feedstock, the size of irreversible investments, as well as price and cost uncertainties will determine whether the proposed lignocellulose conversion will be implemented in a real-world biorefinery. Unfortunately, process design generally disregards the impact of a new technology on the product and feedstock markets, even at later stages of process development. As a result, the economic feasibility of an innovative technology may be grossly miscalculated, possibly compromising its transition from the laboratory to industrial applications. Biorefineries, especially if fuelled by woody biomass, may represent one such case. The entry of a large volume consumer in the competitive market for wood resources may disrupt the existing dynamics of a mature industry. Accounting for these changes could be vital for a successful realization of the envisaged biofuel production chain.

Our study aims to improve the informative value of the current, largely engineering-based process design with the addition of an explicit link to its main feedstock, i.e. woody biomass residues from the forest sector and the wood processing industry. We want to model the impact of an innovative biofuel production process on the wood markets, and thereby determine the economic feasibility of its implementation in an actual biorefinery. In order to achieve this objective, we develop a simplified market model of the forest and wood processing industries, and directly link it to the process design model of an innovative lignocellulosic biofuel component. We thereby try to simulate the impact of biorefineries of the wood markets and estimate how the economic feasibility of the production process may be influenced by the ensuing changes to the feedstock prices.

Currently, there are several techno-economic analyses of biofuels production processes (e.g., He and Zhang, 2011; Maung and Gustafson, 2011; Gnansounou and Dauriat, 2010; Tock et al., 2010; Seabra et al., 2010; Piccolo and Bezzo, 2009; Mao et al., 2010; Sammons et al., 2008), some of them also focusing on woody feedstock (e.g., Ng and Sadhukhan, 2011; Frederick et al., 2008b; Mao et al., 2008; Frederick et al., 2008a). Recent publications have also investigated the economic feasibility of biorefineries (e.g., O'Keeffe et al., 2012; Wu et al., 2010; Leistritz et al., 2006), as well as advances in biofuel supply chain research (An et al., 2011). These studies are based on mass and energy balances followed by various optimization processes that account for cost, size, uncertainty, location and feedstock availability. However, they disregard the mutual influence of markets and the technology they are investigating. Their models generally assume steady-state market conditions, irrespective of the impact a new production process may have on resource availability, market structure, competition for limited resources and prices. These aspects should be adequately accounted for via a complementary economic market model.

In the case of biorefineries, special attention must be paid when solid biomass is the major feedstock resource. Wood is a scarce but essential resource characterized by long-term re-growth patterns and a low energy density. Its supply, which is shared among several mature industries that are characterized by a competitive market structure, can be increased only over a long time horizon (if at all). An excessive short-term exploitation of the available woody biomass resources may lead to unsustainable forest management and eventually price shocks due to disruptive developments. Environmental as well as economic concerns are, therefore, an important component of the design of lignocellulosic conversion technologies, as well as a source of political support.

For our analysis we consider the transformation of beech wood to methyltetrahydrofuran (MTHF), which has been identified as a potential fuel component[1]. Although the individual catalytic reactions and the MTHF's production process are still under development, a preliminary evaluation of the mass and energy balance can be provided by Reaction Network Flux Analysis (RNFA; Voll and Marquardt, 2012a,b) - a screening method for the systematic selection of reaction pathways. The interaction between the biorefinery and the wood markets is accounted for via a spatial partial equilibrium model, a commonly adopted framework of analysis for the dynamics of the forest and wood-based industries. We adapt and calibrate the spatial partial equilibrium platform to the specificities of the German market, where the MTHF biorefinery is assumed to be built in the scenarios considered. The original contribution of this paper is to show the importance of integrating the process design of wood-based biofuels with a market model of their input resources in order to adequately assess their economic feasibility.

The remainder of this article is structured as follows. Section 2 introduces the forest and wood products market model. Section 3 presents the RNFA screening method, while Section 4 explains how the two models are integrated. Section 5 introduces the case study and presents the results of the simulations. In the con-

[1]MTHF is one of the potential biofuel products stemming from an innovative process for the conversion of lignocellulosic biomass into fuels and bulk chemicals currently under development at the research cluster Tailor-Made Fuels from Biomass (TMFB) at the RWTH Aachen University. The envisaged fuels are designed to be blends of well-defined oxygenated components with tailored properties for low-temperature combustion engines.

clusions the main findings are summarized and the strengths and weaknesses of our approach are highlighted.

2 The German Forest Model – GFM

The wood market model has to account for all industries competing for wood resources, to include a realistic wood supply and to endogenously predict the future evolution of price dynamics. In addition, the modeling framework has to allow for the introduction of new technologies in order to evaluate the impact of future wood-based biofuel production. In order to achieve such objectives we base our market model on a spatial partial equilibrium framework.

Before introducing the model, we first present an overview of the current literature on forest and wood markets modeling (Section 2.1). We then proceed to describe the scope (Section 2.2) and formal structure of the model (Sections 2.3), and finally introduce the key parameters and data that underpin the equilibrium condition (Section 2.4).

2.1 Literature overview

Since the 1980s, medium- to long-term developments of the forest sector have been simulated with models based on either spatial partial equilibrium or dynamic optimization.

Spatial partial equilibrium models provide a parsimonious and efficient formulation to simulate the behavior of consumers and producers in competitive but spatially separated markets. Their theoretical foundation traces back to Samuelson (1952), who showed how Enke's formulation of equilibrium between interspatial markets (Enke, 1951) could be related to the linear programming problem of minimum transport costs (Koopmans, 1949) and to the maximization of a "net social pay-off" function[2]. Takayama and Judge (1964a,b, 1971) further elaborated and extended the Enke-Samuelson spatial equilibrium framework, and such approach has been widely applied in the simulation of international trade and resource economics ever since (e.g. McCarl and Spreen, 1980; Norton and Schiefer, 1980).

Early applications of spatial partial equilibrium in the forest sector include the Timber Assessment Market Model (TAMM; Adams and Haynes, 1980), the Forest Sector Prototype Model (FSPM; Lönnstedt, 1983a,b), the Global Trade Model (GTM; Kallio et al., 1987) and the Cintrafor Global Trade Model (CGTM Cardellichio et al., 1989).[3] More recently, researchers have aimed at expanding the inter-

[2]Samuelson (1952), p.288.

[3]The Price Endogeneous Linear Programming System (PELPS), which was also used to simulate

national scope of existing models to better capture the large-scale trends that affect forest product markets across aggregate world regions. These include the Global Forest Products Model[4] (GFPM; Buongiorno et al., 2003), and the European Forest Institute - Global Trade Model[5] (EFI-GTM; Kallio et al., 2004). Alternatively, the focus has been on a more detailed representation of national or regional markets. The Austrian Trade Model (ATM; Kornai and Schwarzbauer, 1987), the Finnish Forest Sector - Global Trade Model (SF-GTM Ronnila, 1995), the Norwegian Trade Model (NTM; Trømborg and Solberg, 1995; Bolkesjø, 2004) and the French Forest Sector Model (FFSM; Caurla et al., 2010) belong to this group.

Whereas forest models based on spatial partial equilibrium are characterized by a recursive optimization process[6], dynamic optimization models use a rational expectations approach to solve the intertemporal problem. Building on the seminal work of Hotelling (1931) and Solow (1974) on resource economics, they presuppose that the equilibrium solution is found simultaneously for all periods. Berck (1979, 1981) was the first to apply this approach to the forest sector, which was later also adopted in the Timber Supply Model (TSM; Lyon, 1981; Sedjo and Lyon, 1990, 1996; Lee and Lyon, 2004).

In addition to substantial differences in the respective theoretical foundations, dynamic optimization and spatial partial equilibrium models are characterized by distinct modeling approaches of the timber supply and trade flow. Idiosyncrasies in their respective representation of the timber supply are particularly difficult to reconcile. In partial equilibrium models, the timber supply function is based on econometrically estimated coefficients. Demand for wood drives equilibrium prices and the wood harvest level. The latter in turn affects wood availability and the volume of the growing stock in the next period. In dynamic optimization, price and timber volume in the different age classes determine wood supply according to an intertemporal optimization that accounts for growing patterns and discounted timber values across the entire period of analysis[7] (Sohngen and Sedjo, 1998; Sohngen, 1998).

the international trade of forest products (Buongiorno and Gilles, 1984), has been adopted as a platform for several applications. E.g., an early version of the above-mentioned GTM model, as well as the North American Pulp and Paper Industry (PAPYRUS) model (Gilles and Buongiorno, 1987) and its later evolution (NAPAP) (Ince and Buongiorno, 2007). Besides PELPS, a common optimization platform is the Generic Algebraic Modeling System (GAMS; Brooke et al., 1988; GAMS Development Corporation, 2012).

[4]The GFPM also builds on an upgraded version of PELPS.

[5]The EFI-GTM model further develops the GTM and CGTM models with a special focus on Europe.

[6]The model is solved one period at a time (i.e. a static optimization); the solutions are then used to update the parameter values of the model in the next period, and the model is thus recursively applied.

[7]Note that the distinction across age classes is important in dynamic optimization, as older timber is harvested first.

An attempt to combine the two frameworks has been made with the Forest and Agricultural Sector Optimization Model[8] (FASOM; Adams et al., 1996), which links the TAMM model for the forestry sector with the Agricultural Sector Model (ASM) of the US economy (Chang et al., 1992; McCarl et al., 1998). Both the TAMM and ASM models have a price-endogenous, spatial market equilibrium structure. However, the solution of FASOM is found via intertemporal optimization over the entire simulation period, and as such it is considered a bottom-up, dynamic partial equilibrium model. A European version has also been developed (i.e. EU-FASOM; Schneider et al., 2008). In EU-FASOM[9], sub-country inventory levels of forest stocks, tree species and age classes are simulated with the OSKAR model, which is then coupled with the EFI-GTM model for a representation of the wood-based industry. However, unlike the EFI-GTM framework, EU-FASOM is a fully dynamic framework optimizing its objective function across all time periods simultaneously.

Despite the large number of forestry models, to our knowledge there is no single simulation tool that accounts for the regional specificities of the German forest and wood processing industries. Instead, most models aggregate Germany into a larger group of countries referred to as Western Europe[10], or evaluate it as a single nation only[11]. Given the importance of evaluating the introduction of a new production technology on the German wood markets, we decided to develop a forestry and wood products market model based on the most recent production and market data parameters. On the one hand, this approach allows us to evaluate alternative biofuel production volumes and their impact on the German wood markets. On the other hand, the scope of our model is limited in comparison to many of the well established simulation tools. We discuss in greater detail the strengths and weaknesses of our market framework in the conclusion, while the next sections illustrate the scope, theoretical structure and parametrization of our model.

2.2 Scope of the spatial partial equilibrium model

The German forest and wood products market model (GFM) presented here is a recursive optimization framework based on spatial partial equilibrium. Two reasons justify this choice. First, spatial partial equilibrium modeling allows a detailed representation of the vertical markets for forest products, and it can include wood

[8]For an updated version of FASOM, also including greenhouse gases emissions (i.e. FASOMGHG), we refer to Beach et al. (2010).

[9]Note that a peculiarity of the FASOM and EU-FASOM models is their detailed account of land use and land use change, both in the forestry and agricultural sectors. These aspects are otherwise neglected in most forestry models.

[10]As done, for instance, in the GTM model by Kallio et al. (1987).

[11]This is the case for the EFI-GTM model. In the EU-FASOM model, while it is possible to consider a detailed regional subdivision of the territory (i.e. NUTS2), forest-related studies typically use a geographical resolution that does not exceed the country level.

demand originating from biofuel production. Second, we can compare our results and partially benefit from the available literature on the econometric estimation of the model's parameters, as several leading European forest sector models are also based on a similar framework (see, for instance, Toppinen and Kuuluvainen, 2010).

The model includes three regions: South, West and East. The South region corresponds to the federal states of Bavaria and Baden-Württemberg. The West region includes Bremen, Hesse, Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate and Saarland. The East region comprises the federal states of Berlin, Brandenburg, Mecklenburg-Vorpommern, Saxony, Saxony-Anhalt, Schleswig-Holstein and Thuringia. In the description of the model's structure that follows in Section 2.3, subscript i refers to the set of regions I.

In total 17 different commodities are considered: two primary commodities (w), six intermediate commodities (s), and nine final commodities (f). The set of final commodities (F) directly purchased by the consumers includes fuel wood, sawnwood, three types of pulp for the manufacturing of paper and paper products[12], three types of wood-based products[13], and biofuels. Intermediate commodities[14] include wood logs, pulp wood, and wood chips, and belong to the set S. Each intermediate commodity is further distinguished by wood type (i.e. coniferous or deciduous). Raw wood, which is classified as either coniferous or deciduous within set W, represents the model's primary commodity (w). The sets of commodities F, S and W are subsets of K, where subscript k denotes all commodities included in the model.

The commodities are manufactured by 21 different production activities. The logging of roundwood produces wood logs, pulp wood and fuel wood. Wood logs are further processed in sawmills to obtain primarily sawnwood. The sawing process also generates wood chips, a by-product that can be resold to other manufacturing activities. Wood chips are primarily derived from pulp wood via a chipping process[15]. Wood chips are then employed as main input in the wood-panel and pulp sectors. The wood-panel sector includes chip board mills, medium-density fiberboard factories and oriented strandboard manufacturing facilities, while the pulp sector accounts for mechanical, sulphite and sulphate pulp mills. All production activities also account for the different types of wood employed (i.e. coniferous vs. deciduous). Finally, we also include a production activity for ligno-cellulosic biofuel,

[12]Mechanical pulp, sulphate pulp, and sulphite pulp.

[13]Chip boards, medium-density fiberboards, and oriented strandboards.

[14]Intermediate commodities are used for the production of final commodities, but are not directly purchased by the representative consumer agents. Instead, they are purchased by the producers of final commodities.

[15]Note that wood chips are derived from pulp wood, as pulp wood is cheaper than wood logs. However, an additional production activity included in the model would allow the conversion of wood logs into chips in case the demand for wood chips is sufficiently high. This ensures that the price of pulp wood will never be higher than the price of wood logs, as one would expect.

whose specific characteristics are determined by the process design model discussed in section 3. Formally, each production activity is represented by subscript l, and belongs to set L. In addition, subscript m identifies the main output of a certain production process, given that in some cases by-products may be sold in the market as well.[16]

2.3 Formal structure of the model

In any given region the equilibrium is found by maximizing the objective functions of three representative agents: a consumer, a producer and a trader. Each region is endowed with specific resources and production capacities, where consumers and producers behave rationally and maximize their respective surplus[17], while traders are concerned with the profit arising from price differentials across regions net of transportation costs. The solution to the optimization problem is found when the model is solved simultaneously for all regions. Based on the formulation of Kallio et al. (2004) and dropping the time subscript for clarity of exposition, the optimization problem then simplifies to the following formulation:

$$\begin{aligned} \max_{\boldsymbol{q},\boldsymbol{h},\boldsymbol{y},\boldsymbol{e}} \sum_{i,f} \left(\alpha_{i,f} q_{i,f} + \frac{1}{2} \beta_{i,f} q_{i,f}^2 \right) - \sum_{i,w} \left(\alpha_{i,w} h_{i,w} + \frac{\beta_{i,w}}{\gamma_{i,w}+1} h_{i,w}^{\gamma_{i,w}+1} \right) \\ - \sum_{i,l} c_{i,l} y_{i,l} - \sum_{i,j,k} D_{i,j,k} e_{i,j,k} \end{aligned} \tag{1}$$

subject to

$$q_{i,f} - \sum_l a_{i,f,l} y_{i,l} + \sum_j (e_{i,j,f} - e_{j,i,f}) = 0 \qquad \forall i, f \tag{2}$$

$$- \sum_l a_{i,s,l} y_{i,l} + \sum_j (e_{i,j,s} - e_{j,i,f}) = 0 \qquad \forall i, s \tag{3}$$

$$- \sum_l a_{i,w,l} y_{i,l} - h_{i,w} + \sum_j (e_{i,j,w} - e_{j,i,w}) = 0 \qquad \forall i, w \tag{4}$$

$$0 \leq y_{i,l} \leq V_{i,l} \qquad \forall i, l \tag{5}$$

$$L_{i,j,k} \leq e_{i,j,k} \leq U_{i,j,k} \quad \forall i, j, k \tag{6}$$

$$h_{i,w} \leq g_{i,w} \qquad \forall i, w \tag{7}$$

where $\boldsymbol{q},\boldsymbol{y},\boldsymbol{h},\boldsymbol{e} \geq 0 \quad \forall i, j, k.$

[16] E.g., the main activity of sawmills is to transform wood logs into sawnwood, but in the process wood chips are also produced, which can in turn be sold to the market.

[17] The consumer surplus for a given commodity corresponds to the area underneath the demand curve and above the price level. The producer surplus is included in the area above the supply curve and below the price level.

The first term in eq. (1) represents the cumulative area under the consumer's demand function for amount $q_{i,f}$ of final commodity f in region i. The model assumes that the representative consumer in each region has a linear and separable demand function with no substitution effects, such that the inverse demand function[18] of each final product equals $\alpha_{i,f} + \beta_{i,f} q_{i,f}$.

The second term of the objective function expresses the area under the wood supply curve. The volume and type of wood w harvested in region i is denoted by $h_{i,w}$. Following the modeling approach of Kallio et al. (1987), the marginal supply cost function for a given amount of harvested wood $h_{i,w}$ equals to $\alpha_{i,w} + \beta_{i,w} h_{i,w}^{\gamma_{i,w}}$, where $\alpha_{i,w}$ is an exogeneous cost component, $\beta_{i,w}$ is a shift parameter and $\gamma_{i,w}$ is the inverse supply elasticity of timber[19].

The third term in eq. (1) corresponds to the total cost of the current production output due to commodities not directly included in the model. The production of all commodities other than wood is symbolized by output $y_{i,l}$ of production activity l in region i, while $c_{i,l}$ summarizes the cost per unit of output due to exogeneous factors (e.g. labor, energy, etc.). Finally, $D_{i,j,k} e_{i,j,k}$ expresses the shipping cost $D_{i,j,k}$ of exporting a volume e of commodity k from region i to region j, where k may refer to final (f), intermediate (s) or raw (w) wood commodities.

An important characteristic of the model's structure is that the production of final commodities is based on bottom-up engineering specifications, which in turn also determine the consumption of intermediate products as well as the harvest level. The input-output requirements are expressed by the matrix of coefficients $a_{i,k,l}$. Given that commodity m is the main output of activity l, and assuming that only the set of final (F) or intermediate (S) commodities belongs to the set M, then $a_{i,k,l}$ equals to 1 for $k = m$, $a_{i,k,l}$ is less than or equal to 0 for inputs $(k \neq m)$, and $a_{i,k,l}$ is greater or equal to 0 for by-products $(k \neq m)$.

In addition, the model's equilibrium solution is subject to a set of constraints. First of all, the solution must ensure that the amount of consumption and exports of a given commodity k in region i equals its total production and import volume. These material balance conditions[20] for final (f), intermediate s, and raw wood w commodities are represented by eqs. (2)–(4), respectively. In addition, capacity

[18] The quantity demanded is generally expressed as a function of price(s). The inverse demand function, in contrast, indicates the price consumers are willing to pay as a function of the quantity demanded.

[19] Note that under perfect competition, the inverse supply function corresponds to the marginal cost function of a given product. In addition, following Kallio et al. (1987) and Kallio et al. (2004), the model actually assumes that $\alpha_{i,w}$ equals 0.

[20] It is important to notice that the shadow prices of material balance conditions corresponds to the domestic equilibrium prices.

constraints on the volume of output ($V_{i,l}$), as well as upper ($U_{i,j,k}$) and lower ($L_{i,j,k}$) boundaries on the volume of trade across regions need to be respected (i.e., eqs. (5)–(6)). Finally, the harvest volume has to be smaller than the growing stock of wood (i.e., eq. (7)).

Problem (1)–(7) is repeated over time in a recursive fashion. In each period, a solution is found without taking into account its impact on the next generation's allocation of resources or the expected net social payoff of its agents[21]. As such, in each time period the equilibrium condition represents a "static" solution. However, the market equilibrium builds on the results of the previous simulations. There are two main factors that affect the evolution of the market equilibiurm across the time periods. First, the exogenously determined GDP growth rate influences the demand for final product f based on the consumer's income elasticity in region i. Second, changes to the harvest value over time affect the growing stock of wood $g_{i,w,\bar{t}}$.[22] The next period's growing stock is driven by the growing rate $\delta_{i,w}$ of the current stock level and the wood harvest $h_{i,w,\bar{t}}$ at time $\bar{t}$, such that

$$g_{i,w,\bar{t}+1} = (1 + \delta_{i,w})\, g_{i,w,\bar{t}} - h_{i,w,\bar{t}} \quad \forall i, w. \tag{8}$$

In particular, the availability of wood resources ($g_{i,w}$) alters in turn the tightness of the wood supply by affecting its supply shift parameter ($\beta_{i,w}$), and hence ultimately also influencing wood prices. In addition, in each period the observed volume of consumption and the corresponding price level are used to recursively update the parameters of the demand function for final commodities (i.e., $\alpha_{i,f}$ and $\beta_{i,f}$). We do not present here in detail the equations undelying the recursive estimation of the above-mentioned parameters, as a more detailed description is already available (Kallio et al., 2008).

2.4 Model specifications

Besides its scope and formal representation, the wood markets model also includes several parameters meant to capture the technical specifications of both the production and transportation sectors, as well as behavioral characteristics of the representative agents. In the next subsection we present in more detail the parameters used in the transportation sector, the elasticity values related to the consumer preferences, and finally the model calibration, which draws on observed production and consumption volumes within the forest and wood products industries.

[21]The agents are assumed to be "short-sighted" (myopic) and do not consider the implications of their actions on their future expected welfare.

[22]Section 4 explains in more detail the different time notation used in the GTM ($\bar{t}$) and RNFA (t) models.

2.4.1 Transportation costs

Transportation costs play an important role in the determination of a price equilibrium among spatially separated markets. In practice, logistics of roundwood and wood products vary according to the distance traveled (see Table 1), the transport medium (road, water ways, rail), and the type of product considered. In addition, in the case of roundwood, a sophisticated analysis may also take into account the wood type (e.g. softwood or hardwood) and debarking (see Table 2).

For simplicity, the model considers only road transport[23] and does not distinguish between wood types. Also, we cannot determine the exact distance traveled between the wood harvest location and subsequent processing plants. Borcherding (2007), Mantau et al. (2002) and Wegener et al. (2004) report that the average transport distance for roundwood and other wood-based products ranges between 77 and 199 km. The model, therefore, makes the simplifying assumption that the average transport distance for commodities originating and consumed in the same region is 50 km, while the average distance for commodities transported across two different regions is 350 km. Since most wood products are manufactured and consumed in the same region, the average distance traveled is within the range proposed in the current literature.

For the unit transport cost values the model refers to the data reported by Borcherding (2007). These estimates proved to be consistent with the cost rates offered by a private wood logistics firm (Witte, 2011) and those reported in other studies (Eberhardinger, 2010; von Bodelschwingh, 2005).

It should also be mentioned that roundwood logistics are more complex and costly in comparison to finished wood products. As such, the model on the one hand assumes that the per unit shipping cost rates of sawnwood and wood-based panels are 23% cheaper than roundwood. Wood pulp and the three different types of pulp products, on the other hand, are subject to transport fees that are 19% lower than those for roundwood.

2.4.2 Elasticities

The long-run projections of the equilibrium model require reliable estimates of price and income elasticities of demand for forest sector products. These parameters capture the responsiveness of the representative consumer to changes in the price of a given commodity or to changes in the consumer's income, and are included in the demand function for final commodities, as illustrated by Kallio et al. (2008).

Unfortunately, to our knowledge, there are no econometric studies that specif-

[23] As reported by Borcherding (2007), p.20, road transport accounts for about 80% of roundwood logistics.

Table 1: Transport costs of air-dried roundwood

Distance [km]	Cost per tonne of air-dried* roundwood [€ /t]	Average cost per tonne of air-dried* roundwood per kilometer [€ /t·km]
25	6.04	0.2417
50	7.77	0.1553
100	11.07	0.1107
200	16.33	0.0817

[a] Air-dried roundwood refers to *lufttrockenes (LUTRO or L) Holz*, which generally entails a 12-15% water content. Dry roundwood corresponds to *absoluttrockenes (ATRO or A) Holz* and has no water content.
Source: Borcherding (2007), p.55–56

Table 2: Conversion factors of air-dried roundwood with dry, debarked and barked roundwood across different wood types

Wood Type	Tonne of air-dried roundwood	Tonne of dry roundwood	Cubic meter of debarked roundwood
Spruce and fir	1	0.545	1.2
Other softwoods	1	0.571	1.2
Beech	1	0.6	0.9
Oak	1	0.643	0.9
Other "hard" hardwoods	1	0.563	0.9
Other "soft" hardwoods	1	0.562	1.0

Source: Lohmann (2003) and Landesforstverwaltung Nordrhein-Westfalen (2000), as cited in Borcherding (2007), p.53

ically estimate the elasticity parameters associated with consumption patterns of wood commodities in Germany[24]. As second-best alternative, we consider the values estimated for countries that share common characteristics with Germany.

Recent studies that estimated key elasticity parameters of wood-based commodities include those of Michinaka et al. (2011, 2010), Kangas and Baudin (2003) and Simangungson and Buongiorno (2001). Michinaka et al. (2011, 2010) performed a cluster analysis in order to allocate 180 countries into separate groups on the basis of the relationship between per capita GDP, forest coverage and per capita consumption relative to selected forest products. Subsequently, they conducted a panel data analysis over the 1992-2007 period and adopted both a static and a dynamic model, each estimating short- and long-run price and income elasticities by pooled OLS, fixed effects or random effects estimations. Table 3, column (d), lists their

[24] The reason for this may be the lack of data on domestic prices of wood products.

Table 3: Price and income elasticities of demand for forest products in various publications

Product	Price elasticity (a)	(b)	(c)	(d)	Income elasticity (a)	(b)	(c)	(d)
Fuelwood	-1.98				0.98			
Sawnwood	-0.20			-0.79	1.04			0.97
Coniferous sawnwood		-0.44				0.19		
Non-coniferous sawnwood		-0.24				0.44		
Plywood	-0.25	-0.53		-1.75	0.99	0.92		0.98
Particleboard	-0.02	-0.15	-1.17	-0.03	2.20	1.09		0.60
Fiberboard	-0.02	-0.97	-0.33	-0.03	0.80	1.22		1.00
Newsprint	-0.17	-0.38	-0.51	-0.14	1.04	0.69	1.82	1.00
Printing & Writing paper	-0.27	-0.25		-0.69	1.15	1.35	1.15	0.93
Other paper	-0.10	-0.16		-0.15	1.05	1.02	0.56	1.10

Source: (a) Simangungson and Buongiorno (2001); (b) Kangas and Baudin (2003), for Western European countries (incl. Germany); (c) Kangas and Baudin (2003) for Germany; (d) Michinaka et al. (2011) for Germany

best estimation results[25] with respect to the long-term dynamic model.

Kangas and Baudin (2003) adopted a multiple equation approach where demand, supply and trade models are estimated for the largest European countries, though their results for Germany were often limited due to data unavailability (Table 3, column (c)). Alternatively, they also provided the results of a time series cross-sectional model for the Western European countries over the 1965-2000 time span (Table 3, column (b)).

Simangungson and Buongiorno (2001) estimated price and income elasticities of nine forest products in 64 countries[26]. They performed a panel data analysis on a static demand model and a dynamic partial adjustment model over the 1973-1997 period. Pooled OLS, least squares with dummy variables, random effects and shrinkage estimators were used to determine the elasticity coefficients and to compare variations in within-country and between-country regressions. In Table 3, column (a), we list the results of the pooled OLS regression on the static model, which the authors identified as the superior estimates in terms of predictive accuracy.

As shown in Table 3, there is considerable variation in the elasticity estimates

[25] As highlighted in their article, Michinaka et al. (2011, 2010) identify the best estimations of each model based on F-values, coefficient signs, Hausman Test, SBIC and rho values for first-order autocorrelation.

[26] Unfortunately, Germany is not included in the list of countries analyzed.

Table 4: Price and income elasticities of demand for forest products in the GFPM and the GTM models

	Price elasticity		Income elasticity	
Product	GFPM	GTM	GFPM	GTM
Fuelwood	-0.62	0.7	-2.26	-0.2
Sawnwood	-0.16		0.32	
Coniferous Sawnwood		-0.5		1.5
Non-coniferous Sawnwood		-1.2		0.7
Plywood	-0.13	-0.4	0.73	1.3
Particleboard	-0.24	-0.4	1.15	1.3
Fiberboard	-0.52		0.82	
Newsprint	-0.05	-0.3	1.14	0.6
Other printing paper	-0.15	-0.2	1.66	1.2

Source: Buongiorno et al. (2003) for GFPM and Kallio et al. (1987) for GTM

due to differences in the methodology, time frame and countries considered. It is inevitable that the value ultimately used in a model will be to some degree arbitrary. In the sensitivity analysis of the model results presented in Section 5.2, we assess how alternative elasticity estimates would actually influence the outcome of the simulations.

For additional references, we looked at the elasticity parameters adopted in the two most widely used forest and wood products models based on spatial partial equilibrium, the GFPM and the GTM models. In the GFPM model, Buongiorno et al. (2003) allocated constant elasticity parameters, with a very general distinction between high- and low-income countries. In the GTM model (Kallio et al., 1987), differences in price and income elasticities across countries are also related to the level of per capita income, though the GTM accounts for four different income categories. Table 4 summarizes the values used by the GFPM and the GTM models for the highest income bracket, and shows, in this case too, that there is substantial variation in the parameters adopted. We therefore decided to adopt values from the GTM model and Kangas and Baudin (2003). We also allow for some variation for the calibration, but tested our assumptions in the sensitivity analysis.

2.4.3 Calibration

As in any other market simulation tool, a calibration of the model is performed in order to ensure that the initial equilibrium solution[27] matches, to the closest extent possible, real world data. In this section, we provide the various data sources used for the calibration, and explain the steps undertaken to overcome some of the difficulties associated with the model's structure or lack of data. Observed values from 2010 are used as benchmark references. In particular, calibration is performed with respect to the observed volume of felling, consumption and production of the endogenous commodities as well as their market prices.

Felling volume and location is provided in the Holzmarktbericht 2010, published by the Federal Ministry of Food, Agriculture and Consumer Protection (BMELV, 2011). Accounting for current production and consumption is more complex. First, data on production is given only at the aggregate country level[28] (ForesSTAT Database; FAO, 2012), and there are no official statistics related to the consumption of wood-based products. Second, the model does not simulate international trade flows.

By keeping in mind the limitations posed by the model's structure and the objective of our research, a solution[29] to the above-mentioned problems is proposed. Most importantly, the model must include the full demand for wood chips arising from their use as feedstock in the production of various wood-based commodities. Wood chips and their price are indeed the key link between the market and process design models. In order to fully assess how the inclusion of a market model may affect the results of the process design of a specific biofuel production technology, it is necessary to account for the aggregate demand for wood chips, even though part of the wood chips consumption is destined for the manufacture of commodities that are exported outside of Germany. Calibrating the parameters of the demand function uniquely based on domestic consumption would either underestimate part of the forces driving production (i.e. for commodities that are exported) or exaggerate the pressure on domestic manufacturers to produce a sufficient output (i.e. for commodities that are actually imported from abroad). In particular, trade flows play an important role with respect to fiberboards[30] and chemical (sulphite and

[27] By initial equilibrium solution we refer to the very fist simulation, i.e. in the first simulation period, when no biofuel plant is built yet. The model is solved recursively for the remaining time periods, based on parameters given.

[28] The Federal Ministry of Food, Agriculture and Consumer Protection does not disclose data on production volume at the federal state level. In addition, information contained in the Wood Market Report is usually consistent with data provided by ForesSTAT, though the latter provides more disaggregated product statistics (FAO, 2012).

[29] Obviously, the lack of an adequate representation of the international trade flows of wood products affects the model's solution. Even though the omission of international trade is admittedly flawed, it is justifiable for the purpose of this research and in light of the limited scope of the case study considered.

[30] By considering fiberboards as the aggregate of medium-density fiberboards and hardboards,

sulphate) pulp, while it is less significant for the remaining commodities included in the GFM model[31].

The model is, therefore, calibrated by matching total consumption of fiberboards and chemical pulp to their respective total production. As such, total consumption for 2010 includes exports of fiberboards, and excludes imports of chemical pulp. The reason for excluding imports of chemical pulp is that production facilities of chemical pulp are already running at close to full capacity. Including imports in the parameterization of domestic consumption would put an additional strain on the price of pulp (and wood chips), while the latter is curbed in reality by imports from abroad. On a similar note, excluding fiberboard exports from the calibration of domestic consumption would create the opposite effect.

The regional distribution of fiberboard consumption is estimated as follows. Net consumption (total production minus exports) is allocated across the federal states according to their respective shares of total population. The remaining additional consumption (total net exports) is assigned to the model's regions according to their respective shares of total fiberboard production capacity. Consumption of pulp (net of total imports) is distributed according to the location of paper production sites[32]. Concerning the calibration of demand for the remaining commodities considered in the GFM model, aggregate consumption is assumed to match aggregate production in 2010, and the regional division is again based on the respective share of total population[33].

For the coniferous and deciduous roundwood prices[34] in the South, West and East regions of Germany we take as references published values from the federal states of Bavaria, North Rhine-Wesphalia and Brandenbung, respectively (StMELF, 2010; Landesbetrieb Wald und Holz NRW, 2010; LFB, 2011). Additional information is also obtained from the Neues Holz Journal (2010). Reference prices for pulp are taken as average import prices in the third quarter of 2010 (EUWID, 2011a), while prices for sawnwood and wood-based panels are directly obtained from various

net exports amounted to 65% of total fiberboards production in 2010, and averaged a share of net exports to production of 42% over the 2000–2010 period (FAO, 2012).

[31]Net exports as a share of domestic production are rather small for both sawnwood and particleboards, respectively amounting to 13% and 3% in 2010 and averaging 7.4% and 10.9% over the 2000-2010 period. Mechanical pulp had a share of net imports to domestic production of 4.8% in 2010 and an average share of 3.5% over the 2000–2010 period (FAO, 2012).

[32]The only end-consumer of pulp, either chemical or mechanical, are paper and paperboard mills.

[33]Obviously, this solution is imperfect. It is dictated by the lack of data on consumption and by the fact that the model does not account for international trade. However, as mentioned in footnote 31, their respective shares of net trade to total production are relatively small.

[34]Note that roundwood prices may differ according to both wood type and quality. The model uses values from the 2b class for coniferous wood logs, and from the B4–6 class for deciduous wood logs. The reference price is estimated as a weighted average with respect to total felling volume in relation to the different tree species included within the coniferous (pine, spruce, fir) and deciduous (oak, beech) wood categories.

Internet sources. Due to the availability of sawnwood, wood-based panels or pulp across the entire German territory, there are no significant price differences across the three regions of the GFM model.

Finally, two last parameters are crucial for the evolution of the model's solutions over time: the growth rates of the wood stock and the exogenously estimated GDP growth rates. The wood stock growth rates are extrapolated from the projected estimates for potential roundwood availability (i.e. coniferous and deciduous) over the 2003–2042 period (BMELV, 2002). Changes of GDP over time are assumed to match the regional historic growth rates over the 2000-2010 period[35] (Destatis, 2012a).

3 Extension of the market model and determination of wood demand for biofuel production

The wood demand for the biofuel production is estimated by the Reaction Network Flux Analysis (RNFA; Voll and Marquardt, 2012a,b). RNFA is a model-based screening method developed for the systematic selection of reaction pathways in the early stage of process design focusing on the entire value chain. A reaction pathway is defined as the combinations of all reaction steps required for the formation of a desired product from a certain feedstock. After the most attractive pathways are identified by mathematical optimization according to a certain objective, they can be ranked by multiple technological, economic and ecological evaluation criteria. In the following, we only provide a brief introduction to understand the key concepts underlying the RNFA model, which should suffice to understand how the RNFA model has been integrated with the spatial partial equilibrium model of the forest and wood products market. Detailed information about the model formulation, solution strategies and evaluation criteria can be found in Voll and Marquardt (2012a,b).

Following the general procedure, all possible reaction steps for the production of a desired target molecule are summarized in a reaction network, starting from different types of biomass or biomass-derived intermediates. This network represents the superstructure of the optimization problem, including possible reaction pathway alternatives. The networks should be built on a comprehensive literature review, but might also contain reactions that are not yet experimentally demonstrated but

[35] Between 2000 and 2010, the GDP per person increased by 8.4% in the South, 8.8% in the West and 14.9% in the East region, taking 2000 as the index year (Destatis, 2012a). These values are equivalent to an annual growth rate of 0.81%, 0.85% and 1.40% in the South, West and East regions, respectively. Over a 5-year period (the time step of the GFM model), a change in GDP relative to the base year would be equivalent to 4.1%, 4.3% and 7.2% in the South, West and East regions, respectively.

that are either proposed by experts in the field or based on preliminary research results. Furthermore, dedicated software tools could be employed for the automatic generation of reaction networks to assess the potential of completely new reactions. Only the reaction stoichiometry must be known to formulate the mass balances and to perform the analysis. The material balances for each substance in the reaction network can be summarized in terms of a matrix equation. The optimal problem then reads as:

$$\min_{\boldsymbol{f},\boldsymbol{b}} \quad \phi \tag{9}$$

$$\text{subject to} \quad \boldsymbol{A} \cdot \boldsymbol{f} = \boldsymbol{b} \tag{10}$$

$$\boldsymbol{f},\boldsymbol{b} \geq 0. \tag{11}$$

Here, the matrix $\boldsymbol{A}$ contains the stoichiometric coefficients of all reactions. The vector $\boldsymbol{f}$ represents the reactive molar flows through the network and $\boldsymbol{b}$ indicates the molecular amount of product and by-product formation. The objective function ϕ can be chosen according to the actual application. In the context of this work, the maximization of the net present value is targeted (i.e., ϕ=NPV). Supplementary information like reaction or separtion yields can be incorporated to improve the significance of the results. Furthermore, at least one input or product stream must be specified to avoid infinite reaction flows. These constraints are then cast in additional equations. Finally, optimal reaction pathways can be detected by solving the optimization problem (eqs. (9)–(11)), thereby determining the values of reaction and product flows as free variables. This also includes the amount of required feedstock and the amount of the final product.

For the integration with the wood market, we mainly focus on economic aspects. In the early design stage, a rough economic evaluation can be based on a preliminary estimation of the NPV, considering revenues and investment cost as main factors in the production of bulk chemicals. Revenues can be calculated by balancing raw material costs and product sales, if the corresponding prices of the specific substances are known. In terms of RNFA, the equation can be formulated as:

$$R_t = b_{prod} M_{prod} p_{prod} - \sum_{raw} (\boldsymbol{A} \cdot \boldsymbol{f})_{raw} M_{raw} p_{raw} \ , \tag{12}$$

in case of a single product. Here, R_t stands for revenues, which might vary for the individual time steps t, and the indices *prod* and *raw* for *product* and *raw materials*, respectively. Furthermore, M indicates the molar mass of the substances and p their prices (in €/kg). The price of wood as major feedstock is transfered from the market model and updated accordingly. In addition, the investment costs IC can be estimated according to a correlation estimated by Lange (2001) based on the energy losses ΔE of the process:

$$IC = Invest1 \cdot \Delta E^{Invest2} \ . \tag{13}$$

Lange determines parameters $Invest1$ and $Invest2$ to be $3 \cdot 10^6$ and 0.84, while the energy loss (in MW) can be calculated from

$$\Delta E = \sum_{raw} (\boldsymbol{A} \cdot \boldsymbol{f})_{raw} \left| H_{com,raw} \right| - b_{prod} \left| H_{com,prod} \right| \ , \tag{14}$$

where H_{com} are the substances' enthalpies of combustion at standard conditions. Finally, the investment cost still need to be updated to today's price level by the chemical engineering plant index and converted into €. After that, the NPV of the process can be estimated as:

$$NPV = \sum_{t=0}^{t_{run}} (R_t - IC) \left(1 + \frac{i}{100}\right)^{-t} \ , \tag{15}$$

if the interest rate i and the run time t_{run} of the plant are given. This equation can be simplified, if the revenues are constant over time for one initial investment, but the RNFA model can also be solved in each time step t of a planning horizon. Then, temporal changes in the parameters (e.g. in prices, yield coefficients or product demands) can be captured, which might affect the (time-variant) selection of reaction pathways, material and product flows. As a consequence, additional (temporal) constraints might be required, depending on the assumptions of the particular case study, e.g., to limit the product flow according to the installed production capacity.

4 Integration of the GFM and RNFA models

The integration of the GFM and RNFA models is performed as a bi-level optimization problem via the Generic Algebraic Modeling System (GAMS; Brooke et al., 1988; GAMS Development Corporation, 2012).

First, the RNFA model is solved in order to determine the demand of wood required for a given volume of biofuel output.[36] The wood feedstock demand remains constant across all simulation periods thereafter.[37] The GFM model then simulates

[36]The feedstock demand is optimized on the basis of the feedstock prices simulated by the GFM model in the first period. In the first period, the biofuel plant is under construction and no biofuel is yet sold to the market.

[37]We could have also programmed the integration of the two models differently, i.e., allowing the RNFA model to optimize feedstock demand in each simulation period, in order to minimize feedstock costs and maximize the NPV based on the expected price level. However, three reasons prompted us not do it. First, in order to highlight the contrast with current models, we wanted

the ensuing wood markets' equilibrium *ex-post* the introduction of the new lignocellulosic production chain. In doing so, the GFM model determines the price level of the wood feedstock. Based on the varying price level of the feedstock, the NPV of the biorefinery is estimated.

The GFM model further assumes the level of biofuel consumption is set to match the output capacity of the biorefinery. It is expected that the demand for biofuel is far greater than the production level simulated, and that the oil and other energy markets would hardly be affected by it[38]. The volume capacity of the biorefinery as well as the type of feedstock and input mixes may be varied in alternative scenarios. The GFM model can thereby assess the impact of alternative production processes on the wood markets.

The new price prediction of the GFM is incorporated into the RNFA model in order to update the expected cost of its woody feedstock (indicated by p_{wood}[39] as one type of raw material in the RNFA model) and evaluate its yearly cash flows. The initial capital investment and the cash flows generated by selling the biofuel and paying for its feedstock inputs are discounted over the 20-year time interval to determine the NPV of a given biorefinery (i.e. $t = 1, \ldots, 20$ in eqs. (9)–(15)).

It must be mentioned that, as common practice in most forestry models, the GFM is solved over 5-year time intervals, denoted by $\bar{t}$.[40] The price prediction generated by GFM is, therefore, used in the RNFA model as the average price of raw inputs over a 5-year spell. Every 5 years, the GFM generates a new price prediction based on the exogenously determined GDP growth rate of the economy, the current wood stock and its growing rate, the use of wood resources, and the evolution of consumption and production of the various wood commodities.

Formally, at any point $\bar{t}$ the GTM model solves its objective function (eq. (1)) subject to the constraints (eqs. (2–6)), as described in Section 2.3, and a level of biofuel consumption ($q_{i,biofuel}$) fixed by the scenario modeled ($\bar{\boldsymbol{q}}$). The RNFA model determines the input coefficient ($a_{i,s,biorefinery}$) required by a biorefinery in region i, based on the type of feedstock s, for one unit of biofuel output. This coefficient can be determined by the quotient of f_{wood}/b_{prod}. Given the exogenously determined level of biofuel consumption and the corresponding demand for woody biomass inputs, the model finds an equilibrium solution that accounts for the response of the remaining

to resemble the current process design modeling approach, where no economic market modeling is included. Second, the feedstock price increment is so high that the end result would probably have not changed significantly. Third, it is always difficult to estimate *a priori* how flexible a biorefinery's production facilities actually might be.

[38] An adequate representation of the oil and other energy markets is beyond the scope of this analysis.

[39] Note that the term "*wood*" is rather generic and may refer to different wood types (i.e. conifer or deciduous) or wood inputs (e.g. wood logs, wood chips, etc.).

[40] $\bar{t}$ is such that $\bar{t} = t$ for $t = 1, 5, 10, 15, 20$. This is equivalent to saying that, in their respective simulation time frames, $\bar{t} + 1$ equals $t + 5$.

endogenous commodities. The equilibrium solution also determines the price of woody biomass inputs (p_{wood}) used in the biofuel production, in order to estimate the actual NPV of the biorefinery simulated by the RNFA model.

5 A case study based on 2-methyltetrahydrofuran

We implement the approach described in the previous section to evaluate the process design of 2-methyltetrahydrofuran (MTHF). MTHF is considered a novel biofuel component, which could potentially replace standard fuels. It can be produced from woody biomass (i.e. beech wood) via levulinic acid followed by a consecutive series of hydrogenations and dehydrations (see Figure 1, and Geilen et al., 2010).

We assume that the biofuel plant is located in West Germany and has an expected lifetime of 20 years, which include a building phase of 5 years and a run time of 15 years. For simplicity, fuel demand and fuel prices are not yet calculated by a market model, but instead assigned according to reasonable estimates. More specifically, the pre-tax fuel price of MTHF is fixed at 0.59 €/l and relates to current diesel prices in Germany under the assumption of fuel price parity based on energy content. We thereby assume that the output of MTHF is small in relation to the total fuel demand, and that the entire output will be sold to the fuel markets without influencing the fuel price. As such, in the GFM model, consumption of biofuel is fixed in order to match total MTHF production.

Deciduous wood chips are used as raw material inputs for the production of MTHF. Biofuel production competes with the pulp and wood-based panels sectors for the use of wood chips. While the RNFA model determines the input demand for wood chips associated with a given MTHF production level, the GFM model estimates the market response and determines the price level of the input feedstock, which allows to estimate the profitability of a biorefinery of a given size. In addition, the model implements alternative scenarios where plant capacity is varied between 50×10^3 and 500×10^3 tonnes of biofuel output per year. The exact volume requirements for biofuel production in the various scenarios is given in Table 5, which lists the solution of the RNFA model for different fuel amounts.

5.1 Results

The market model simulates the price of deciduous wood chips in the West region to equal €13.4[41] in 2010. Over the next 20 years, the price of wood chips is expected

[41] A price of €13 for wood chips is consistent with current market prices. See for instance EUWID (2011b), p.7. The price of wood chips and sawdust in Germany between Oct. 2010 and Oct. 2011 ranged between €10.5 and €16.5.

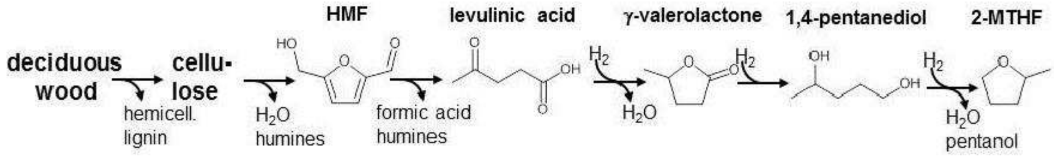

Figure 1: The wood conversion process

Source: Based on Marquardt et al. (2012)

Table 5: Deciduous wood chips volumes required to produce some given quantities of MTHF output

Scenarios	Biofuel yearly output [t·yr^{-1}]	Input of decid. wood [m$^3\cdot$yr^{-1}]	Biorefinery NPV without market response [million €]	Biorefinery NPV with market response [million €]
Base	0	0	0	0
1	50,000	580,518	2.3	-27.3
2	100,000	1,161,036	36.5	-89.2
3	200,000	2,322,071	130.1	-1180.6
4	300,000	3,483,107	241.1	-2120.4
5	400,000	4,644,142	362.5	-4873.6
6	500,000	5,805,178	491.4	-8715.9

Source: Own simulation results based on RNFA and GFM models

to increase by about 30% to €17.4[42]. The price increment is due to the exogenous GDP growth rate, which drives the demand for various wood products upwards. Producers will react to the higher demand for final commodities by raising output, and put an upward pressure on the price of intermediate commodities such as wood chips.

Under the assumption that biofuel production from woody biomass would not affect the price of wood chips, the profitability of MTHF biofuel plants would turn out to be positive for all plant sizes taken into account. In addition, the larger the plant, the greater the NPV estimate (see Table 5).

However, the arrival of a high-volume consumer of wood chips offsets the existing market dynamics. As shown in Figure 2, the price of deciduous wood chips in the West region after the introduction of biofuel production increases significantly[43].

[42]Such a price increment is actually a conservative estimate in comparison to the current evolution of wood chips prices. Between 2005 and 2009, the price of industrial beech wood increased by more than 50% (Destatis, 2012b).

[43]Figure 2 expresses the average price of deciduous wood chips over the 5-year time interval that follows the introduction of MTHF production (after the initial 5-year plant building phase).

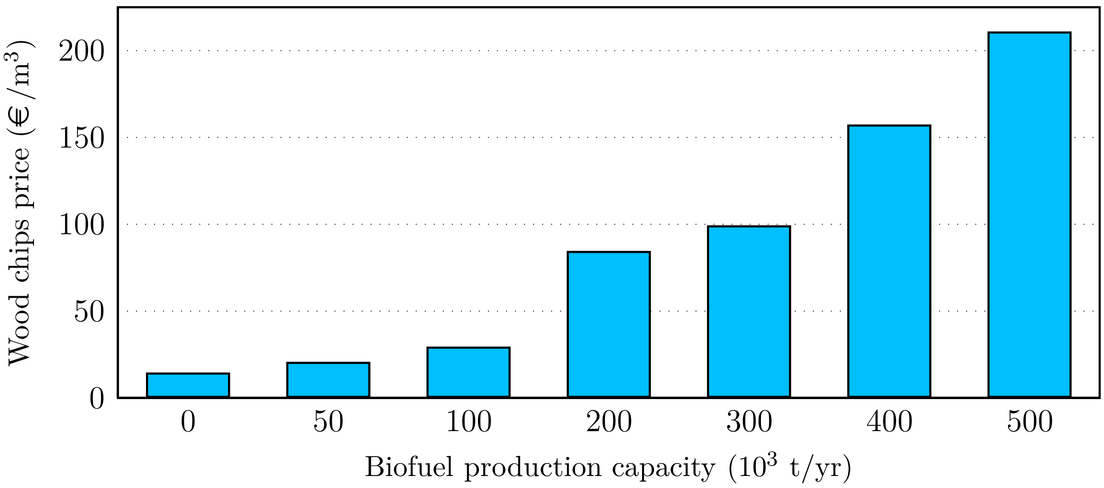

Figure 2: Prices of deciduous wood chips in the West region after the introduction of biofuel plants with different capacities

Source: Own simulation results

The smallest plant taken into consideration (i.e. 50×10^3 tonnes of biofuel output per year) leads to a wood chips price level that is 41% higher than in the base scenario[44]. Larger plant sizes widen the price differential even further. As a result of the price increment, no biofuel plant, irrespective of its output capacity, turns out to be profitable. Note that this result differs markedly from that for the case where the RNFA process design model disregards the impact of the new technology on the resources market.

Such a price response is, among other elements, contingent on the volume of wood chips available. According to our optimization, biofuel production requires an amount of deciduous wood chips that ranges from 3% to 28% of the total wood chips consumption in the base scenario. However, deciduous wood chips constitute only a small share of the total. In 2010, coniferous trees amounted to 77% of the total felling volume[45] (BMELV, 2011). Similarly, deciduous wood chips contribute to only 22% of the total wood chips used as intermediate feedstock. As a result, even the smallest biofuel plant consumes an amount of wood chips equivalent to 13% of total deciduous wood chips use in the base simulation. A biofuel output of 200,000 tonnes per year would require 50% of the total deciduous wood chips available in the base scenario.

[44]Note that an output capacity of 50×10^3 tonnes of biofuel per year is estimated to require about 705×10^3 m^3 of deciduous wood chips. Such a large consumption volume goes beyond what any wood chips company we contacted would have been able to deliver. The largest commission of beech wood that we could find was listed in the Neues Holz Journal (2010), Nr. 2010/24, p.3. There it was reported that ForstBW (Baden Württemberg) had agreed to deliver 45,000 t of industrial beech wood for a new price of 73.25€/t.

[45]Our simulation for 2010 is consistent with this result, where felling of coniferous trees amounts to 78% of the total.

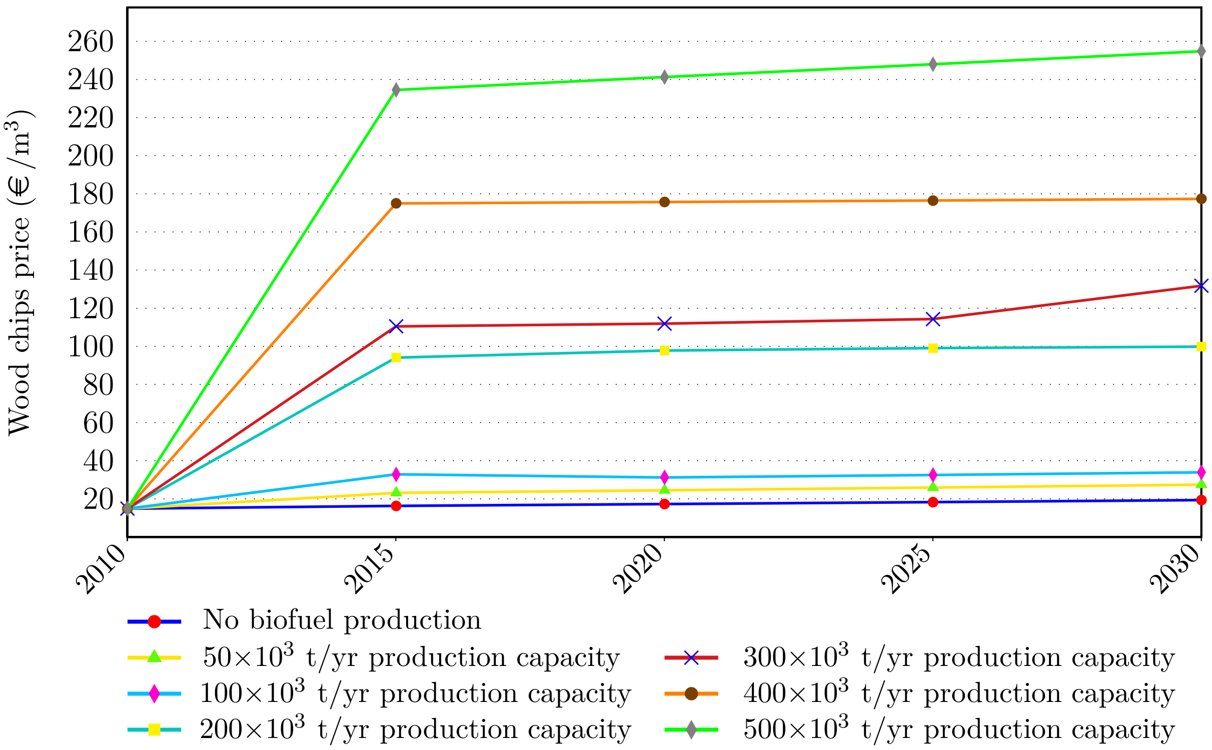

Figure 3: Evolution of deciduous wood chips prices for the different scenarios

Source: Own simulation results

Given the size of feedstock consumption, it is not surprising to observe such a marked rise in its price, especially when also taking into consideration the competition for resources coming from other wood processing sectors. Obviously, imports of deciduous wood chips would play an important role and partially curb the price increase caused by the introduction of a wood-based biofuel manufacturer. Nonetheless, the volume of deciduous wood demand remains too large in relation to its aggregate domestic availability to assume that the price of deciduous wood chips will not be affected.

A final remark concerns the evolution of prices that result from the introduction of the new technology. After the initial price adjustment, the model's new equilibrium solution is updated in the ensuing periods according to the already mentioned GDP growth. Since there are no further shocks simulated by the scenarios, the model expects a mild price growth, as shown in Figure 3.

5.2 Sensitivity analysis

The robustness of the market model's results has been tested via a sensitivity analysis of key exogenous variables. The parameter values have been individually altered by ±15%. In particular, the sensitivity analysis accounted for income and demand elasticity of each final commodity, elasticity of the wood supply curve, transport costs, GDP growth, and the growth rate of the wood stock.

In most cases, the key result of our optimization (i.e. the price of deciduous wood chips in the West region) does not change by more than 5%. Notable exceptions are the demand elasticity of sawnwood and chip boards, the elasticity of wood supply as well as the transport costs of wood chips and fiberboard products. In the most extreme case, there is a price differential of about 30%, relative to the first period of base scenario with no biofuel production[46].

It is not surprising that variations in the above-mentioned elasticity parameters play a significant role in the equilibrium solution, especially given the relative importance of sawnwood and chip boards in the model's framework. Sawnwood consumption determines the demand for wood logs, which in turn drives wood felling[47]. At the same time, wood felling affects the availability of pulp wood, which is converted into wood chips for the production of various final commodities, including biofuel. Therefore, an increase (or decrease) in the responsiveness of sawnwood consumption to changes in sawnwood prices affects wood log demand, wood felling and, ultimately, the availability of wood chips. The availability of wood chips is then reflected in their price. Based on the calibration of our model, the price of deciduous wood chips changes by about ±10–12%[48]. Besides sawnwood, wood chips prices also respond strongly to changes in the demand elasticity of chipboards. Chipboard factories are the main consumer of wood chips (34% of total), a relationship that is even stronger in the West region (56% of the total). As a results, adjustments to its demand parameters have a significant impact on equilibrium prices[49].

The transport cost of wood chips and fiberboard products also influence the equilibrium price. In our base simulation, the West region exports wood chips to the East region[50], where they are employed for the production of sulphate pulp, MDF and OSB. Lower transport costs put a higher pressure on the demand for

[46]The two most extreme cases are represented by a lower supply elasticity of roundwood, and a lower demand elasticity of chipboards

[47]Wood felling is primarily due to the demand for wood logs, given that felling produces primarily wood logs (85%), followed by and pulp wood (12%) and fuel wood (3%). The model further assumes that, besides pulp wood, also wood logs can be converted into wood chips. However, since wood logs are expected to be much more expensive than pulp wood, the latter case occurs only in extreme scenarios (e.g. in the last scenario, when biofuel output amounts to 500,000 tonnes per year).

[48]The price of wood chips changes from €13.37 to €12.00 (+15%) or €15.02 (-15%). Note that these values refer to changes with respect to the base case. In addition, the ±10–12% change in wood chips prices is associated with the first period of the simulation. The price differential decreases over time to about ±3–6% in the last simulation run. The new prices are €16.76 (+15%) or €18.23 (-15%) instead of €17.40. This occurs because part of the response driven by the new demand elasticity is compensated by the increase in sawnwood production stimulated by the exogenous economic growth.

[49]Wood chips prices in the West region vary from -18% (€10.9) to +29% (€17.4), relative to the first period of the base scenario. The introduction of MTHF production gradually reduces the gap to the base scenario, the larger the biofuel plant taken into consideration.

[50]Note that both the West and South regions export wood chips to the East region.

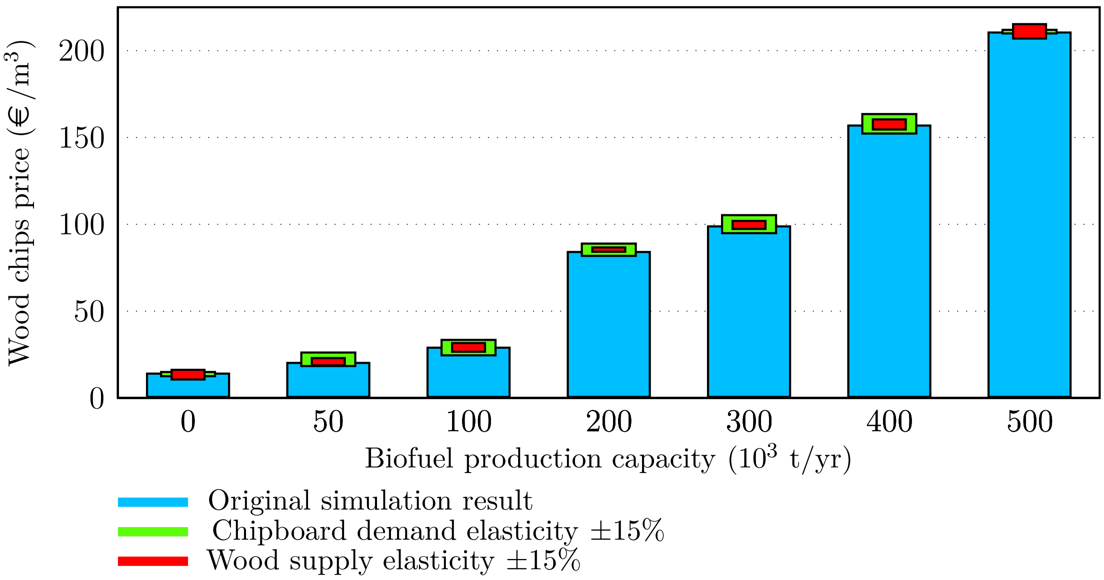

Figure 4: Prices of deciduous wood chips in the West region after the introduction of biofuel plants with different capacities and error bars

Source: Own simulation results

wood chips and push wood chips prices upwards[51]. Besides wood chips, the West region also exports chipboards to the East region, so that changes to the shipping rates of fiberboard products are ultimately reflected also on the price level of its feedstock input[52].

Finally, the sensitivity analysis shows that the price elasticity of wood supply[53] affects the marginal cost of wood chips. The model assumes an elasticity of 0.5, a value commonly used in other simulation models (e.g. Kallio et al., 2008; Kallio et al., 1987), and that is consistent with the estimates based on recent econometric studies (e.g Hänninen et al., 2006; Bolkesjø and Solberg, 2003). The responsiveness of the wood supply to price changes affects also the value of one additional unit of wood chips, which varies by about 20%.

Despite what may seem to be large variations, in the first period of the simulation the price of wood chips remains reasonably close to the observed price level, which ranges between €10.5 and €16.5 (EUWID, 2011b). Figure 4 also shows potential changes to the price of wood chips across all scenarios. The original price of deciduous wood chips is coupled with error bars symbolizing the results obtained with

[51] Prices increase by 12% compared to the base scenario. Higher wood chips transport costs, on the other hand, do not have the same impact, and do not alter the price of wood chips significantly.

[52] The model assumes that all panels and fiberboard products have the same per unit cost of transport. Variations of ±15% in their shipping rates have an impact of about ±8% relative to the deciduous wood chips price of the base scenario.

[53] The marginal cost of harvesting, which also represents the supply of roundwood, is modeled as $C_{i,w}(h_{i,w}) = \beta_{i,w} h_{i,w}^{\gamma_{i,w}}$. Thus, $1/\gamma_{i,w}$ represents the price elasticity of roundwood. Note that in the simulation we vary $\gamma_{i,w}$ by ±15%, instead of varying the actual value of the roundwood supply elasticity. Nevertheless, the results would not differ significantly.

alternative values for the elasticity of wood chips demand and the elasticity of wood supply[54]. As can be seen from Figure 4, the deviations from original equilibrium decrease, in relative terms, for larger biorefineries. Most importantly, however, the main insight arising from the introduction of MTHF production does not vary in the sensitivity analysis. That is, the profitability of the biorefinery, irrespective of the size of the plant, remains negative. In addition, the larger the capacity output, the closer the price response of the model is to the original scenario. This highlights the fact that the shock in prices, driven by the demand for wood chips from MTHF production plants, remains unvaried under alternative parameter assumptions, thereby making investments in MTHF facilities unprofitable.

6 Conclusion

Before drawing conclusions with "real world" implications based on the results of this case study, some considerations must be made. The models' simulations would suggest that the production of biofuels from deciduous wood in Germany may be problematic, if at all economically feasible, given the technology's characteristics and resources availability accounted for in this paper. However, such a statement must be interpreted with caution. Above all, the forest and wood products model is a simplified and parsimonious representation of the actual dynamics and forces governing the forest and wood industries. In addition, our analysis does not adequately represent international trade. The simulated price shock of deciduous wood chips is probably overestimated, given that accessible foreign resources are not accounted for.

At the same time, it may be reasonable to argue that a MTHF biorefinery's demand for deciduous wood chips is large in relation to the availability of deciduous wood on the domestic market, and, hence, that prices will be to some degree affected[55]. More in general, however, it must be pointed out that price predictions in response to exogenous shocks (such as the increased demand for renewable for scarce resources due to a new production process) are not only difficult to simulate due to the large number of long-term dynamics and variables involved, but are also strongly dependent on the modeling approach adopted. A similar analysis should, therefore, also be carried out with other forest models, possibly including international wood trade, in order to validate and improve the significance of our results, as well as to corroborate (or dismiss) the outcome of our study.

[54]The elasticity of demand for wood chips and the elasticity of wood supply were chosen for the graphic, since they contributed to the largest deviations from the original values.

[55]In general, biofuel production from coniferous wood is also theoretically possible, though the conversion parameters would be different.

Furthermore, future investigations should also consider additional resources for fuel production (e.g., coniferous wood, or a mixture of coniferous and deciduous wood chips), which could possibly impact the results of this research. Hence, additional case studies are required before drawing final conclusions. Nevertheless, the merit of this paper is its compelling argument for the integration of process design and market models. Our analysis highlights the importance of paying attention to the selection of raw materials and products not only from a technical perspective, but also in view of resource availability, given the competition for raw materials from other industry segments and the existing market structure. In order to assess the economic feasibility of a given production technique and to enable the successful transition from the laboratory to real-world applications, process design models should be complemented with economic market models of key input factors.

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