Biofuel Development and the Competition for Forest Raw Materials: A Partial Equilibrium Analysis of Sweden

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Abstract

In order to reach the renewable energy policy targets in the transport sector, biofuels produced from forest raw materials (e.g., harvesting residues) can be cornerstones. Still, these raw materials are currently used as inputs in the heat and power (HP) sector and in the forest industries (pulp and paper plants and sawmills). It is essential to understand how these sectors would be affected by an increased penetration of second generation (2G) biofuels. Sweden is interesting to study due to its well-developed forest industries and mature HP sector involving intense use of forest biomass. The technological experiences and a well-developed infrastructure also make Sweden a suitable country for future 2G biofuel production. This study investigates price development and resource allocation in the Swedish forest raw materials market in the presence of 5-30 TWh of 2G biofuel production. A national partial equilibrium of the forest raw materials markets is extended with a Bio-SNG module to address the impacts of such production. The simulation results show increasing forest industry by-product (i.e., sawdust, wood chips and bark) prices, not least in the high-production scenarios (20-30 TWh), thus suggesting that the 2G biofuel targets lead to increased competition for the forest raw material. The higher feedstock prices make the HP less profitable, but very meagre evidence of substitution of fossil fuels for by-products is found. In this sector, there is instead an increased use of harvesting residues. Fiberboard and particleboard production ceases entirely due to increased input prices. There is also evidence of synergy effects between the sawmill sector and the use of forest raw materials in the HP sector. Higher by-product prices spur sawmills to produce more sawnwood, something that in turn induces forest owners to increase harvest levels. Already in the 5 TWh Bio-SNG scenario, there is an increase in the harvest level, suggesting that the by-product effect kicks in from start.

Keywords: 2G biofuels, partial equilibrium, competition

1. Introduction

One of the key strategies to combat climate change is to replace fossil fuels with renewable energy sources in the transport sector. During the recent decade, the share of biofuels in the European Union (EU) transport sector has increased from 8.5% (in 2004) to 17% (in 2016) (Eurostat, 2018). However, at present almost all transport fuel is produced from crops grown on agricultural land, so called first generation (1G) biofuels. The resulting competition with food production is worrisome, especially because of possible threats to global food security (Lotze-Campen et al., 2014). For this reason, the global community is currently searching for sustainable biofuel alternatives produced from lignocellulosic biomass and other non-edible feedstocks, so-called second generation (or advanced or next-generation) biofuels, hereafter referred to as 2G biofuels.[1] While an increased use of such biofuels will lead to less intense conflicts with food production, it will instead fuel competition for the forest raw materials. This paper addresses the question of how a policy-driven increase in the demand for such biofuels may affect the competition for raw materials among the various users of forest resources.

On June 14, 2018, negotiators from the European Commission, the European Parliament and the European Council reached a deal on the proposed revised Renewable Energy Directive (REDII), which sets new targets for renewables. The proposed Directive stipulates that at least 14% of the transportation fuel must come from renewable sources by the year 2030, but only 7% can come from first generation biofuels. The share of 2G biofuels and biogas must be at least 1% in 2025 and at least 3.5% in 2030 (EU 10308/18). Forest industry by-products and harvesting residues are considered sustainable, and they therefore constitute promising feedstocks for 2G biofuel production (European Parlament, 2017). However, these resources are scarce, and are currently used in the traditional forest industries as well as in heat and power (HP) production. For the above reasons, 2G biofuel production may be associated with sharply increasing marginal costs. Strong policy incentives for the domestic production of 2G biofuel may have profound impacts on feedstock prices, and in turn lead to a substantial re-allocation of forest biomass across the existing and the new sectors.

[1] Other sustainable biofuels are so called third generation biofuels (produced from e.g. algae), and fourth generation biofuels (e.g. electrofuels) that are not produced from biomass (Aro, 2016; Liew, Hassim et al. 2014). Third and fourth generation biofuels are not further addressed in this paper since the focus of this study is on forest biomass markets.

The purpose of this paper is to investigate price formation and resource allocation in a domestic forest biomass market in the presence of increased 2G biofuel production and demand. This research focus is motivated for three reasons: (1) feedstock costs constitute a substantial share of the total cost of biofuel production (Gnansounou & Dauriat, 2010; Levasseur, Bahn, Beloin-Saint-Pierre, Marinova, & Vaillancourt, 2017; Millinger, Ponitka, Arendt, & Thran, 2017); (2) it reveals how new raw material prices could affect forest industries' production, which in turn affects the by-product supplies; and (3) it indicates whether resources tend to be drawn away from the more mature bioenergy-using HP sector. For these reasons, feedstock price formation is crucial information in order to evaluate the competitiveness of various biofuel production alternatives. By acknowledging the potential market effects from introducing 2G biofuels, the results from this paper can lead to more informed policy decision-making.

In the presence of an increased demand for forest biomass, at least two market effects can be expected: a *competition effect* and a *by-product effect* (Lauri, Forsell, Korosuo, Havlík, et al., 2017). The competition effect is the increased competition for raw materials under a constrained biomass supply. This causes feedstock prices to increase, but by different magnitudes depending on the supply situation for various feedstock. The by-product effect refers to the synergy effect between the forest industries producing by-products and sectors demanding by-products, e.g., plants producing heat or 2G biofuels. When such plants demand more by-products (e.g., wood chips, sawdust, etc.), the prices of by-products increase, in turn generating higher returns to the plant owners supplying these. In addition, this creates an incentive to increase the production of the main product, something that in turn generates more by-products. In other words, whereas the competition effect leads to feedstock price increases, the by-product effect can mitigate such a price rise by inducing an increase in the supply of by-products.

In the paper, we investigate these concepts in the empirical context of the Swedish forest raw material markets. Sweden is an interesting case for several reasons. Productive forest land accounts for 57% of Sweden's land area; the country has a well-developed forest industry sector as well as a mature HP bioenergy sector. The technological know-how together with the existing infrastructure make Sweden a suitable candidate for increased 2G biofuel production using lignocellulosic biomass (Mola-Yudego et al., 2017; Mustapha, Bolkesjø, Martinsen, & Trømborg, 2017). In 2016, the total demand for transport fuel in Sweden amounted to 92.4 TWh (SEA, 2017). As much as 16% (16.9 TWh) originated from biomass. However, the majority of the biofuels were imported 1G biofuels.[2] Sweden has a strong political will to increase the domestic production of sustainable transport biofuels (The Swedish Government, 2016, 2017).

In order to assess the forest raw materials market effects under the introduction of increased 2G biofuel production and demand, scenarios of 5-30 TW 2G biofuel production are assessed in a partial equilibrium forest sector model. Specifically, the so-called Swedish Forest Sector Trade Model II (SFSTMII) is used, updated to the reference year 2016, and extended with a 2G biofuel module including domestic demand and production of such biofuels.

The by-products generated in the Swedish forest industries are to a large extent used in the pulp and paper industry and in the HP sector. Since forest biomass is a scarce resource, introducing 2G biofuel production in Sweden is likely to affect the domestic forest biomass markets and thus the other sectors demanding biomass. Additional demand for biomass can lead to increased or decreased feedstock prices, depending on resource allocation, and the relative magnitudes of the competition effect versus the by-product effect. The outcome depends on the relative price changes of the various feedstocks, which together with the agents' demand functions and technologies determine the feedstock allocation. By identifying changes in resource allocation within and between sectors, as well changes in terms of domestic production and international trade, it is possible to learn more about the market effects of implementing 2G biofuel production targets.

The rest of the study is organized as follows. An overview of the literature is provided in Section 2. The modeling approach, including the original model, the model extensions, and the scenarios, are outlined in Section 3. The simulated scenario results addressing the 5-30 TWh of 2G biofuel demand targets in the Swedish biomass market, including a sensitivity analysis on import levels, are presented in Section 4. Finally, Section 5 provides a discussion of the results, while Section 6 summarizes the main conclusions from our analysis and outlines some important avenues for future research.

[2] Hydrotreated Vegetable Oil (HVO) accounted for 68% (mainly produced from vegetable and palm oil). Ethanol accounted for 7% of total transport biofuel use, out of which 97% originated from edible crops. Raw tall oil, a 2G biofuel, accounted for 7% of total biofuel use. The remaining 18% of biofuels originate from "other" 1G biofuel feedstocks (SEA 2017).

2. Overview of the literature

The majority of previous studies investigating market effects from introducing a biofuel target focuses on the competition for land (e.g., Havlik et al. (2011); Wyatt Thompson, Seth Meyer, and Travis Green (2010). A 2G biofuel target removes the obstacle of land use competition, this since land use does not change with increased production. The main obstacle to increased 2G biofuel production instead relates to production costs, which generally are higher than those for the first generation biofuels. The total production costs for 2G biofuels are in turn largely driven by feedstock prices (Festel, Würmseher, Rammer, Boles, & Bellof, 2014; Havlik et al., 2011). In an extensive report of 2G biofuel production costs, Landälv and Waldheim (2017) conclude that the single most important variable, which influences the overall production cost is the feedstock price. For instance, in HVO production, feedstock costs account for 60-80 % of the total production cost. The feedstock costs for bio-diesel produced from forest biomass is estimated to account for more than 70% of the future total production costs (in 2020) (Festel et al., 2014). Whereas investment (capital) costs typically decrease with increased unit produced (due to scale economies, learning-by-doing, etc.), the share of feedstock costs is also likely to increase with increased production (Gnansounou & Dauriat, 2010). In other words, the profitability of 2G biofuel production is heavily dependent on feedstock prices, and this makes feedstock price formation particularly relevant to study.

Söderholm and Lundmark (2009) discuss some conceptual issues of the competition for forest raw materials; price formation and resource allocation. They distinguish between three separate product categories: main products, co-products, and by-products. Although all products are produced simultaneously, their market characteristics differ. The market for the main product is the key determinant of production levels. Yet, if co-products are required to make the production for the main product economic, the market for these co-products will influence production decisions. By-products are produced in association with the main product and co-products, but they do not influence production levels since they are a spill-over product and will be produced regardless of its market price. Contrary to the definitions introduced by Söderholm and Lundmark (2009), the modeling setting in this paper will allow by-products to influence the levels of main products produced, i.e., essentially implying that products that have been byproducts may become co-products. Specifically, the production functions will include by-products and the endogenously determined market prices for these. Whether by-product prices will affect the main product levels or not is therefore an empirical question, and this is further discussed in Section 5.2.

Lauri, Forsell, Korosuo, Havlik, et al. (2017) investigate the forest biomass market implications of reaching the 2 °C global climate target. They find that higher biomass demand for energy can be achieved without significant distortions to the forest biomass markets. They explain this resultby referring to the by-product effect, i.e., increased use of forest biomass for energy increases the demand for sawmills' by-products. This makes the sawmill industry more profitable, and compensates for the cost effect of increased competition over raw materials. Lauri, Forsell, Korosuo, Havlik, et al. (2017) describe their finding as an inverted U-shaped function effect where woody biomass material use depends on the trade-off between the by-product and the competition effect, respectively. Thus, similar to the present study, Lauri, Forsell, Korosuo, Havlik, et al. (2017) allow for by-product to influence the production levels of the main production.

When analyzing an increased EU demand for wood pellets, Jonsson and Rinaldi (2017) find both by-product effects and increased competition between wood-based products and wood pellets. They find that sawmills benefit from an increase in wood pellets demand. Whereas both Lauri, Forsell, Korosuo, Havlik, et al. (2017) and Rinaldi (2017) assess the forest biomass market from an international perspective, the present study assesses the effects of EU policies on a domestic market. For our purposes, the domestic forest biomass market is disaggregated into a range of main forest products, intermediate products and by-products. The empirical focus on a single country thus permits a more in-depth assessment of the various links between the sectors using forest raw materials. In a study about the Norwegian forest biomass markets, Trømborg, Bolkesjø, and Solberg (2013) investigate how 2G biofuels made from lignocellulosic biomass may affect the competitiveness of bioheat generation. Similar to the present study, they use a national spatial partial equilibrium forest model. They find that the pulp production shrinks and sawnwood production increases in the presence of a higher demand for 2G biofuels. Moreover, the bio-heat production is reduced by 5-20 percent depending on the 2G biofuel production levels. The latter is an interesting result; if bioheat is reduced in favor of 2G biofuel production, the environmental benefits may be dubious. Sweden and Norway and their forest biomass markets are different in several respects; Sweden has more than three times the amount of productive forest land (SLU, 2018; SSB, 2017), a larger forest industry sector and a mature bioenergy-dependent HP sector. This suggests that Sweden is likely to have a comparative advantage in 2G biofuel production, while this may be less likely for Norway (Mustapha, Trømborg, & Bolkesjø, 2017).

In order to account for spatial differences in forest supply, Ouraich, Wetterlund, Forsell, and Lundmark (2018) develop a geographically explicit price determination model of forest raw materials. An exogenous demand is defined for forest raw materials. Demand is satisfied with supply from the region(s) with the lowest supply cost (based on availability and transport costs). Ouraich et al. (2018) apply this model to Sweden, and assess forest raw material prices under different levels of 2G biofuel demand. Following an increase in 2G production of 30 TWh, almost no price effects in the domestic raw material market are detected. This is explained with the high model resolution, which enables the model to choose feedstock more efficiently (Ouraich & Lundmark, 2018). The model do not consider market interactions between sectors competing for forest raw material.

Leaving out the market interactions could potentially lead to both an under and an overestimate of feedstock prices. Even a small price increase for one feedstock can cause an industry to substitute this feedstock for another feedstock; this pushes up the price of that feedstock, and starts a chain reaction of price changes and altered resource allocations.

In order to assess price formation and the competition for raw materials, a model that includes the various sectors demanding the respective feedstocks is warranted. Carlsson (2011) employs the so-called SFSTMII model with reference year 2008 to investigate the effects of introducing more ambitious bioenergy demand targets in the HP sector in Sweden (5-25 TWh). He finds increasing raw material prices and that increased demand in the bioenergy sector is satisfied with increased use of harvesting residues and pulpwood. The increased demand for pulpwood cause pulpwood price to increase to the levels of sawlogs. When that happens, also sawlogs are used as feedstock in the bioenergy sector. Because additional pulpwood was imported (i.e., no additional supply of harvesting residues), and no increased use of by-products was found, no by-product effects were detected.

To conclude, previous studies have often focused on either 1G biofuels and/or countries as a group. Moreover, this study accounts for market effects, i.e., interactions between sectors and industries via prices. Unlike Carlsson (2011), and in line with the so-called waste hierarchy established in Directive 2008/98/EC, and re-established in the proposed REDII directive (EU 10308/18), this paper does not allow chipped pulpwood as a feedstock for energy conversion counted towards the renewable energy targets. This study has a national perspective, similar to Trømborg et al. (2013) study, but assesses the case of Sweden, which is considered to have a great potential for future production of 2G biofuels.

3. Material and method

The primary interest is to analyze the raw material competition at the Swedish forest biomass market in the presence of 2G biofuel demand targets. A number of scenarios are investigated in a partial equilibrium modeling setting, in which the Swedish sawmill, pulp and paper, HP bioenergy and 2G biofuel sector, are described. The demand target scenarios vary between 5 and 30 TWh of 2G biofuels and are compared to the baseline year 2016.

3.1. Modeling approach and data

Lestander (2011) developed the Swedish Forest Sector Trade Model (SFSTM), which is a static forest sector model including forest harvest, forest industry production and the demand for various forest industry products in Sweden. It can be employed to analyze the competition for forest raw materials among sectors in the traditional forest industry (e.g., saw mills, pulp and paper plants). In the model, Sweden is divided into four geographical regions. These four domestic regions trade raw materials and forest industry products with each other, as well as with a region representing the Rest of the World (ROW).[3] ROW is incorporated as a trade partner to the domestic regions in order to reflect international competition for forest biomass and forest industry products. Carlsson (2011) extends the SFSTM model with a HP bioenergy sector module in order to analyze the welfare effects (i.e., consumer and producer surplus) from an increased bioenergy demand in the HP sector. Carlsson's model is referred to as the SFSTMII model.

The SFSTM (as well as the SFSTM II) model consists of two sub-models: one trade cost model that calibrates prices and feedstock allocation to a reference year, and one model that can be used to simulate prices and feedstock allocations under various scenarios. The trade cost model

[3] The ROW includes the EU Member States and Norway.

is a Takayama-Judge (1964) type spatial partial equilibrium model. This builds upon Samuelson's (1952) spatial equilibrium theory of interregional trade in which the net social pay-off for the products and regions included are maximized. In the Swedish forest model, all products can be traded except HP energy and black liquor (a by-product from pulp mills), which are assumed to be consumed in the same region as they are produced. In the second sub-model, net social welfare is calculated as the sum of the area under each demand curve minus production costs in the production sectors, including the sum of transportation costs resulting from trade between regions. Suppliers maximize their profits (producer surplus) and consumers maximize their net benefits (consumer surplus). The sectors relying on forest raw materials are assumed to act in a market characterized by perfect competition. The maximization of producer and consumer surplus provide the equilibrium resource allocation and prices. The modeling structure builds on the same structure of demand, supply and trade as in the global GTM (M. Kallio, 1987) and the EFI-GTM (Maarit Kallio, Moiseyev, & Solberg, 2004) models, as well as in the Norwegian forest sector model NTMII (Bolkesjø, 2004).

The demand for forest industry products (sawnwood, paper and board products) and HP energy are represented with demand functions. Sawlogs, pulpwood and harvesting residues are supplied by forest owners. Production, feedstock allocation within and between sectors, as well as price formation, are endogenously determined. In order to investigate the effect of increased 2G biofuel demand on the existing HP sector and the forest industries, this study extends SFSTMII by implementing a 2G biofuel module, i.e., exogenous demand for 2G biofuels and endogenous production technologies for such fuels using forest biomass as feedstock. How this extension was pursued is discussed in detail in the next sub-section. Figure 1 provides an verview of SFSTMII, including the new module.

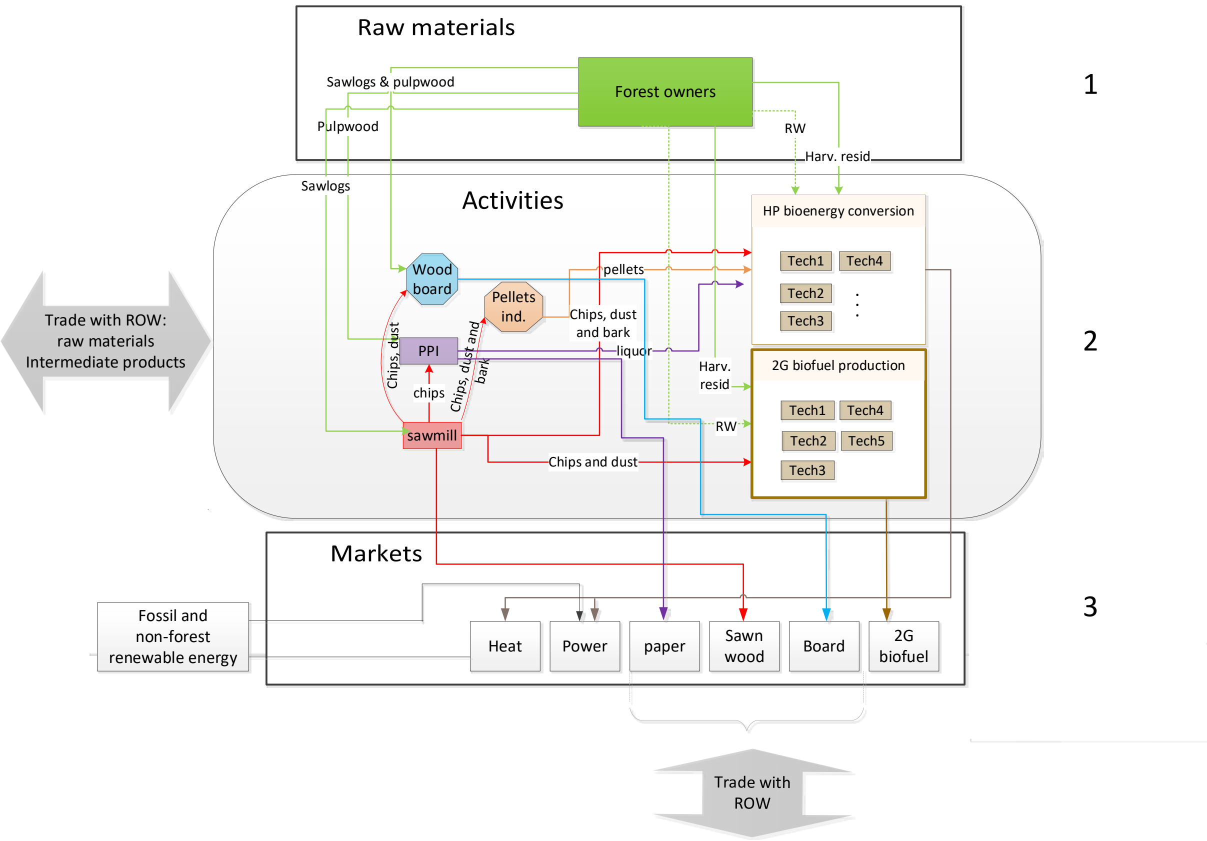

Figure 1: The Swedish Trade Sector Model with 2G production.

The model consists of three parts: the upper box (part 1, Raw materials) depicts forest owners' supply of roundwood and harvesting residues. The middle box (part 2, Activities") shows the part where all the production and conversion processes reside. The underlying production functions are of a Leontief structure, which is represented with fixed input-output (IO) coefficients.[4] The IO-approach is suitable for modeling sectors with agents entangled via many productions paths, and it has been commonly used in the forest sector modeling literature (see (Sjølie, Latta, Trømborg, Bolkesjø, and Solberg (2015)) for a review of forest sector modeling approaches). Since the IO-coefficients are fixed sets (technology and feedstock), there exist no continuous substitution possibilities between various feedstocks. Still, by including several IO-coefficients with different feedstocks for one technology, substitution between feedstocks is

[4] In the literature, Input-output coefficients/analysis is sometimes referred to as activity analysis. All IO-coefficients (except for 2G biofuel) are from Carlsson (2011).

implicitly included and some constrained substitution effects can be analyzed. The boxes to the left in part 2 represent forest industry production, e.g., the production of sawnwood demands sawlogs from the forest owners, and then supplies sawnwood to end-users as well as by-products (e.g., wood chips, sawdust and bark) to the pellets industry, bioenergy sector and the 2G biofuel sector. The upper box to the right in part 2, (Tech 1, Tech 2,…etc.) shows the bioenergy used in the HP conversion sector (e.g., conversion technologies using different feedstock). The lower box to the right in part 2 (Tech1-Tech5), represents the production of 2G biofuels, i.e., one technology in combination with different feedstock options.

The bottom box (part 3, Markets) in Figure 1 depicts the demand for final products: HP, 2G biofuels, and forest industry products such as paper and board products and sawn wood. The model is driven by the demand for final products, which in turn leads to an endogenous demand for raw materials, intermediate products and by-products. The demand function for HP and forest industry products is defined in Equation 1.

$$D_{i,f} = \widehat{D}_{i,f} \left(\frac{P_{i,f}}{\hat{P}_{i,f}}\right)^{\varepsilon} \qquad (1)$$

where *D* is the endogenously determined quantity. The index *i* corresponds to the region in which the demand takes place, whereas the index *f* corresponds to which product is demanded (e.g. HP and sawnwood). The parameter $\widehat{D}$ refers to the reference demand level (observed demand for the reference year), and is used as a start value in the calibration model. *P* is the endogenously determined price and varies with feedstock costs. The parameter ε is the own-price elasticity with regard to the price. For forest industry products, ε ranges between -0.60 and -0.17. The ε for HP is -0.3. The demand for HP can be satisfied with either fossil fuels or bioenergy.

Finally, the model can trade with ROW (indicated with large grey arrows in Figure 1). The model will choose to import a product if the import price is lower than domestic production costs plus transport costs (given that demand exceeds supply). If the domestic consumer market is saturated for a product, and domestic production is cost competitive with ROW production, then the product will be exported to the ROW. ROW Baseline product prices are, similarly to the remainder of the model, calibrated to 2016 data on the use and production of products. Since the domestic market is relatively small from an international perspective, ROW prices will not be affected by changes in the Swedish market. The model is programmed in the General the Algebraic Modeling System (GAMS), and the CONOPT solver is used both for the transportation cost minimization problem and the welfare maximization problem.

3.2. Implementing a second-generation biofuel technology module

Various 2G biofuels differ in terms of properties, production costs, environmental performance and accessibility. Furthermore, the same biofuel can vary substantially in performance and cost performance depending on the biofuel production, e.g. plant size, technologies, investment time frame. In addition to the disparate biorefinery processes and fuel properties, techno-economic estimates of the production costs of 2G biofuels tend to differ substantially due to methodological differences (e.g. assumed interest rate, system boundary assumptions, etc.). This makes it arduous to compare production costs between studies (Carriquiry, Du, & Timilsina, 2011; Gnansounou & Dauriat, 2010; Haarlemmer, Boissonnet, Imbach, Setier, & Peduzzi, 2012). In an extensive review of 2G biofuel production costs, Landälv and Waldheim (2017) identify a cost range of 50-140 EUR/MWh. Fisher-Tropsch liquids production costs range between 90 and 125 EUR/MWh, Biomethane, methanol and DME between 56 and 91 EUR/MWh, HVO between 50 and 90 EUR/MWh, and cellulosic ethanol between 85 and 103 EUR/MWh. These differences originate from assumptions regarding feedstock costs, technology matureness, installation costs and external factors.

In order to keep this study as transparent as possible, only one type of 2G biofuel is included, represented with one biomass-to-yield conversion rate and one investment cost for capacity enlargement. Specifically, 2G biofuel is exemplified with biobased synthetic natural gas (Bio-SNG). The techno-economic potentials of Bio-SNG have been verified in many studies (e.g., (Gassner and Marechal (2012); Gustavsson & Hulteberg, 2016; K. Pettersson et al., 2015). It is impossible to predict which 2G biofuels that will become successful in the market. Bio-SNG is used as the example in this paper due to its great flexibility; both in terms of feedstocks use, and the upgrading possibilities to several different liquid 2G biofuels (e.g. diesel and ethanol). Following (Karin Pettersson, Lundberg, Anheden, and Fuglesang (2018)), we assume a biomass-to-fuel yield of 70% on an energy basis. For the IO-coefficient specification, four feedstocks are available for production in five fixed proportions: 100 % chips, 100 % sawdust, 50% chips and 50% sawdust, 100% pellets or 100% harvesting residues. The respective feedstocks have different energy contents. Table 1 (third column) shows how much of each feedstock is required to produce one MWh of Bio-SNG.

Feedstocks (ton)	**calorific value GJ/ton**	**Ton feedstock for 1 MWh SNG**
Chips	16[a]	0.298
Sawdust	16[a]	0.298
Chips/sawdust	16[a]	0.298
Pellets	17[b]	0.275
Harvesting residues	12[c]	0.387

Table 1: Column two present the feedstocks' calorific values. They are from EECA (2017)[a] , Whittaker, Mortimer, Murphy, and Matthews (2011)[b] and Forest Research (2018)[c]. Column three presents how many ton of each feedstock is required to produce one MWh Bio-SNG.

The Bio-SNG is assumed to be produced in stand-alone plants. If demand increases, and the plant is not producing at its maximum capacity, production may increase according to the assumed conversion and feedstock costs. If the plant is producing at its maximum capacity and demand increases, plant capacity can be increased with an investment cost of 229 EUR/MWh[5], and an annualized factor of σ = 0.08, which is equivalent to a 5% interest rate and a production plant lifetime of 20 years. The size of a Bio-SNG plant is determined by the tradeoff between the economies of scale of larger plants, and increased costs of feedstock transportation. In practice, there is always a minimum plant size to make the production profitable. For Bio-SNG produced in Sweden, the smallest capacity has been estimated at around 100-300 MW (Karin Pettersson et al., 2018). However, since the model builds on the use of Leontief production functions, and substitution of feedstock is only expressed indirectly via fixed sets, the model is at risk to choose corner solutions. This may give rise to lock-in effects in the case of minimum plant size. Considering that it is uncertain which, if any, 2G biofuel that will actually be introduced in the market at any significant scale, it is preferable to avoid such lock in effects caused by big discrete steps in investments. Therefore, plant capacity is in this study allowed to increase in incremental steps of only one MWh. Following Karin Pettersson et al. (2018), the operation and maintenance costs are set to 6.2% of the investment cost, i.e., 14 EUR/MWh[6].

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[5] 229 EUR/MWh is an average estimate of a plant investment between 100 MW and 300 MW presented in Pettersson, Lundberg et al. (2018)

[6] In Carlsson (2011), the operation and maintenance costs (labor cost, electricity and other) are assumed to be 27 SEK/m3f of feedstock input, an assumption that was shown to be consistent with the corresponding operation and maintenance costs assumed in Pettersson, Lundberg et al. (2018).

The demand for 2G biofuel is modelled in a similar manner as presented for other final products (Equation 1). However the determined quantity is not allowed to vary (i.e., being endogenously determined) due to exogenous demand targets in the scenario analysis. For modeling technical reasons, all parameters presented in Equation 1 are included also for 2G biofuel demand (i.e., a reference price, quantity produced and own-price elasticity)[7], but their magnitudes are not expected to affect the quantities produced. Similar to the HP sector, the four Swedish regions are not allowed to trade 2G biofuels with the ROW, i.e., the 2G biofuel targets have to be achieved with domestic production. Bio-SNG can be produced and consumed in all four regions. Before end-use consumers, e.g., households, can buy the 2G biofuel at a gas station, further processing of the fuel is required as well as transportation of the fuel to the gas station. These steps of the value chain are not described in the model, this in order to keep the analysis as general as possible in terms of technologies.

3.3. Data

SFSTM and SFSTMII were calibrated to the year 2008. For the present study, all data have been updated and calibrated to the year 2016. Six categories of roundwood are included: sawn timber and pulpwood, both of which can be produced from three species: spruce, pine and non-coniferous. Harvesting data (m^3f) are from SFA (2017), SFA (2018) and FAO Statistics (2018). Forest industry production output (final and intermediate products, i.e., different kinds of sawnwood (m^3), pulpwood (m^3), paper (ton), fiberboards (ton), and pellets (ton) are from SDC (2017), FAO Statistics (2018), The Swedish Forest Industries (2018), CEPI (2017), IEA Bioenergy (2017), BET (2017), The Swedish Pellet Association (2017), and the European Pellet Council (2018).

By-product prices are from SCB (2017). No data on harvesting residues are available; instead estimations of quantities harvested (1.716 Oven Dried Ton (ODT)), available quantities and the price of 818 SEK/ODT have been drawn from Carlsson (2011). Roundwood prices are from

[7] As no commercial facilities for bio-SNG production were in operation in Sweden in the reference year (2016), an arbitrary low level Bio-SNG production is assumed across all four regions as a proxy for the current state. The reference price of Bio-SNG is approximated with the production cost for the lower level of Bio-SNG production, averaged across feedstocks (67 EUR/MWh), presented in Pettersson, Lundberg et al. 2018. For Bio-SNG, ε is set to being fully inelastic (i.e., vertical).

UNECE (2018) and FAO Statistics (2018). According to the reference values, demand for final products is mostly located in south Sweden. The reference levels for HP use are based on population density data from Statistics Sweden (2018). Feedstock composition in the HP sector (MWh) is gathered from the Swedenergy (2016) and SDC (2017). The fossil fuel price for the energy sector is assumed to be equivalent to the price for heavy oil, which was 6601 SEK/MWh (about 70 EUR/MWh) in the year 2016 (SPBI, 2018).

Due to imperfections in harvesting data (unreported thinning, imprecise weighing, estimations etc.) and the modeling assumption made to include only EU and Norway to represent ROW[8], shortages of roundwood and forest industry by-products occur in the calibration model. Following Carlsson (2011), an exogenous supply of forest biomass is added to cover up for material imbalances.[9] An exogenous supply of 5.5 m^3f millions of pulpwood has been added, which makes total harvest in the country reach 73 million m^3f. Actual net harvest is 74 m^3f million ton. The last million cubic meter harvest is neither logs nor pulpwood, and is categorized as “other”. For the ROW, 13 million m^3f of logs and 19 million m^3f of pulpwood are added to the model. No exogenous by-products had to be added to the Swedish market. During the past 10 years, the EU Member States have experienced a substantial increase in the overall imports of wood chips, sawdust, wood pellets, etc., from non-EU countries. Between 2005 and 2015, such imports increased by approximately 270 %, reaching 14 million tons in 2015 (Eurostat, 2018). Net-imports of wood pellets to the EU from non-EU countries increased by 79% between the years 2009 and 2016.[10] Since this development is not reflected in the model, an exogenous supply of by-products has to be added to the ROW; 94 million m3f sawdust and 115 million m3f wood chips were therefore added to the ROW part of the model.

Another explanation to the difference between demand and supply in the ROW is the assumed IO-coefficients, which are assumed to be the same for all the countries included in the ROW region, but may vary considerably between countries. As Carlsson (2011) points out, another alternative to address the shortage in the ROW would be to adjust the by-product

[8] Restricting the definition of ROW to the most frequent trade partners prevents the model from generating misleading simulation results based on aggregated forest data, e.g., roundwood from tropical species with other energy content than represented in the model.

[9] Exogenous supply is calculated in a similar manner as in Carlsson (2011): production multiplied with the IO-coefficients gives the required input. In the example of sawnwood, that is: sawnwood production multiplied with the IO-coefficient for sawnwood gives the harvest of sawlogs.

[10] The main suppliers of EU imports were the United States and Canada; much less has been supplied by Russia and other countries (Eurostat 2018).

coefficients from sawn goods production in the ROW region. However, doing that would imply differences in the relative competitiveness between Swedish and ROW sawn goods production when the prices of these by-products change. Full tables of exogenous supply including tree species are presented in the Appendix (Table 2-3).

The inclusion of exogenous supply will affect the resource allocation in the model. Although the numbers come from observed discrepancies, some products can be produced with more than one feedstock and therefore, the numbers are not necessarily entirely correct. In order to investigate the impacts of the added exogenous feedstocks, a sensitivity analysis was conducted with different proportions of exogenous roundwood species and wood chips/sawdust to cover the material imbalances. The results in the calibration model were shown to be robust to roundwood species but sensitive to the proportions of by-products. In the latter case, if more wood chips (or sawdust) was added, the price of wood chips decreased and more wood chips (or sawdust) was utilized in the model. This is an expected result; by-products are expected to be more price sensitive than roundwood since their own-price elasticities of supply are expected to be low (Söderholm & Lundmark, 2009). More importantly, the relative order of the prices of products was shown to be stable across exogenous feedstock levels, and therefore the exogenous supply should not be expected to introduce any structural biases in the scenario analysis.

3.4. Scenarios

The baseline scenario (Baseline) is simulated given data for the year 2016. Production of manufactured forest products and HP, as well as trade of raw material and products, are simulated. The baseline scenario thus reflects the Swedish forest raw materials market when no large-scale 2G biofuel demand and production has yet been implemented.

Import levels of raw materials are constrained to 2016 import levels. Between 2012 and 2016, EU imports of wood pellets from non-EU countries increased by almost 80% (reaching almost 8000 million tons) (Eurostat, 2018), due to increased feedstock demand for pellets in the HP sector. With current policies, this development is expected to continue (Balan, Chiaramonti, & Kumar, 2013), followed by increased competition and increased feedstock prices (Johnston & van Kooten, 2016; Jonsson & Rinaldi, 2017). Thus, it is unrealistic to assume all countries to satisfy increased demand for biomass with increased imports. For this reason, the import levels in the various scenarios are constrained to those observed in 2016. The effects of relaxing this import restriction is analyzed in a separate sensitivity analysis (Section 3.2).

The baseline prices of sawdust and bark are lower compared to observed data. Because by-products do not come with a production cost, there is no lowest price limit for which these products can be supplied. The lowest price for which trade will occur is the cost for transportation of the by-products. The price are formed in direct response to demand. Moreover, given that the model does not include every small sector that demands sawdust, the model finds an oversupply which makes the price lower compared to observed data. However, the relative price order of sawdust, bark and the other raw materials are identical with observed data.

In addition to the baseline scenario, a number of scenarios that involve various 2G biofuel demand levels are investigated. The future renewable transport fleet is expected to constitute a mix of different 2G and 1G biofuels, and other types of vehicles, not least electric cars. Moreover, significant efficiency measures to reduce the overall energy demand for transport can also be anticipated. Still, 2G liquid biofuels are expected to be particularly important in greening heavy transports, and the aviation sector (Bessou, Ferchaud, Gabrielle, & Mary, 2011; EU 10308/18; Mustapha, Trømborg, et al., 2017). In July 1st 2018, Sweden introduced a so called Biofuel obligation scheme to reduce emissions in the transport sector (similar to countries like Germany, Brazil and Canada). The Swedish biofuel obligation scheme requires fuel suppliers to reduce emissions in gasoline and diesel by blending non-renewable fuels with environmentally sustainable biofuels (Julia Hansson, Hellsmark, Söderholm, & Lönnqvist, 2018; The Swedish Government, 2018).

In this study, a range of 2G biofuel production, from 5 to 30 TWh in steps of five representing different future developments, is investigated. This range corresponds to 4-25% of current total fuel demand in the Swedish transport sector (and 5-33% of the road transport fuel demand). In line with the Biofuel obligation scheme, these 2G biofuel targets force the market to consume 2G biofuels.

The simulated results will be presented in the following order. First, the model's choice of feedstocks used to produce Bio-SNG is outlined – the triggering factor for all subsequent events. Secondly, as the Bio-SNG industry and the HP energy sector are competing for the same feedstock, the feedstock composition in the HP sector is assessed. Thirdly, the forest industry sector's production is assessed; this is linked to price changes caused by 2G biofuel production and any feedstock composition changes in the HP sector. The range of 5-30 TWh Bio-SNG is investigated and compared to the baseline level (i.e. no Bio-SNG production). Each scenario (5, 10, 15 TWh…) is thus compared individually to the baseline, e.g., the output for 10 TWh of Bio-SNG is compared to the baseline. In addition to the main results presented and discussed, a sensitivity analysis is conducted in which the role of imports of raw materials is assessed.

4. Scenario results

4.1. Results

Figure 2 shows the feedstock composition in Bio-SNG production for the scenarios ranging between 5 and 30 TWh. Raw sawdust is used for low levels of Bio-SNG production, while pellets (mainly processed sawdust, Figure 3) dominate for the larger production levels. Pellets is cheaper to transport than sawdust due to its higher energy content per ton, but comes with a relatively low intermediate production cost. The model's first hand choice is pellets. As a response to the increased demand for pellets in Bio-SNG production (and the constraint on pellets import), domestic pellets production shoot up after 10 TWh of Bio-SNG production (Figure 3). The initial decline is explained by decreased pellets exports due to an increased pellets price in the domestic market. The use of pure sawdust for low levels of Bio-SNG is likely due to usage of locally supplied sawdust (i.e., with low transport costs). The use of sawdust, raw or processed to pellets, is explained by its relatively low price and high energy content (compared to harvesting residues, etc.).

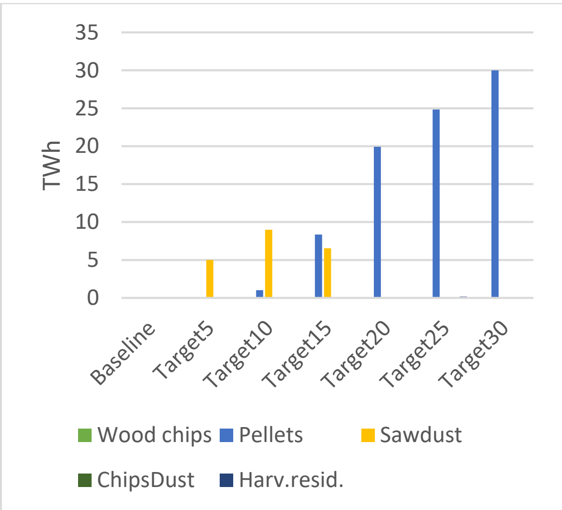

Figure 2: Feedstocks used in the production of 5-30 TWh Bio-SNG.

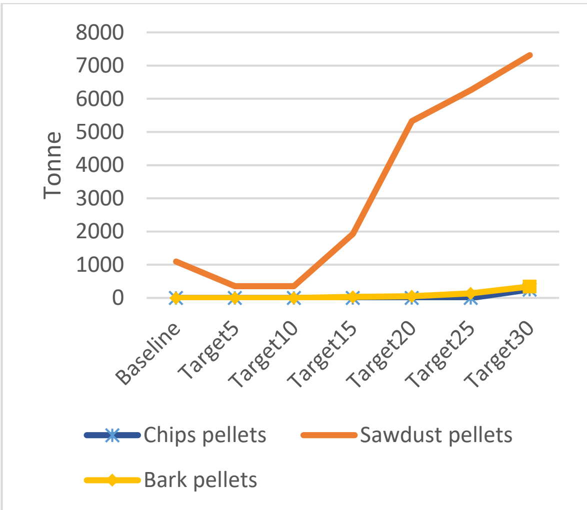

Figure 3: the pellets industry, production in tonne.

Figure 4 shows the domestic price developments of forest industry by-products and pellets for the different Bio-SNG scenarios. The price formation curve behaves as expected, i.e., it is increasing slowly in the presence of low demand levels but becomes steeper when the respective feedstocks are close to reaching their supply constraints. For instance, the supply of the by-products (e.g., sawdust) will be constrained by the production level of the main product (e.g., sawn wood). Figure 4 also provides an indication of how much additional 2G biofuel demand that can be imposed before feedstock prices soar, which in this case seems to be when 20 TWh of Bio-SNG is added to the market demand.

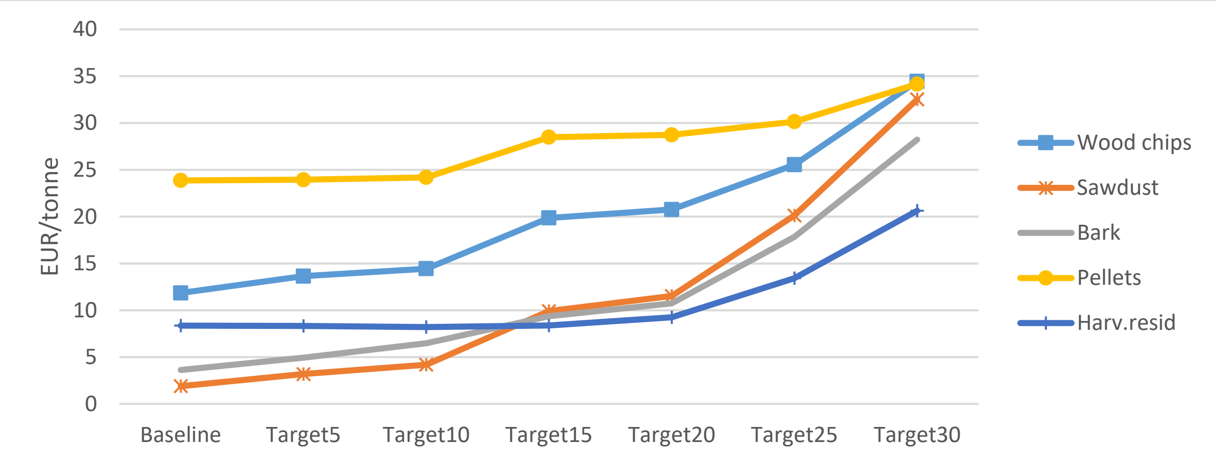

Figure 4 Price development of forest industry by-products and pellets under 5-30 TWh Bio-SNG demand. Wood chips, sawdust, and bark are recalculated to dry tonne with the conversion factor 0.29 and with 2016's exchange rate 9.5 SEK/EUR.

Figure 5 shows the feedstock composition in the HP sector for 0-30 TWh of Bio-SNG production. The total production of HP is assumed to be constant over all scenarios (own-price inelastic demand). However, which feedstock-technology set to satisfy the production is perfectly elastic; i.e., the feedstocks used in the HP sector will vary with feedstock prices. In the HP sector, biomass fuels compete with fossil fuels supplied in unlimited quantities at an exogenously given price.

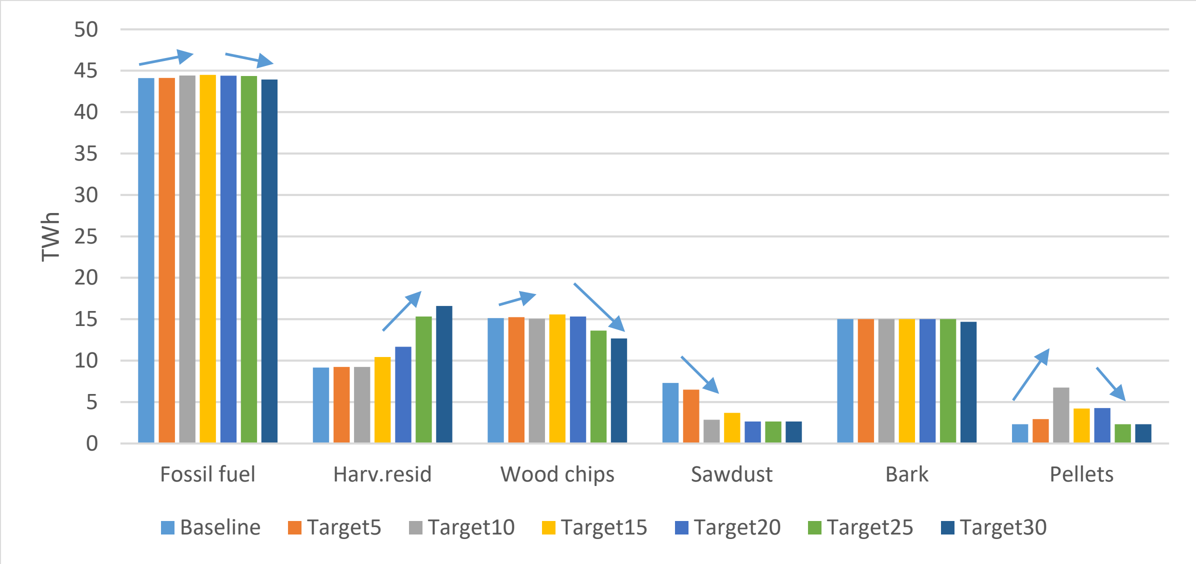

Figure 5: Feedstock composition in the heat and power sector in the presence of 0-30TWh Bio-SNG. The total amount of heat and power production is constant across scenarios.

As shown in Figure 5, the use of sawdust in Bio-SNG production has consequences for the HP energy sector's feedstock composition, for which sawdust decrease the most. The use of sawdust decrease already at 5 TWh of Bio-SNG production. The feedstock shortage is covered up by pellets, a development that stops at 10 TWh due to rising by-product prices. In addition, the uses of sawdust and wood chips are cut back due to the price increases. Comparing the 30 TWh Bio-SNG scenario with the baseline (i.e., no Bio-SNG production), a total feedstock shift of 7.5 TWh is observed in the HP sector; the use of sawdust is reduced by 4.7 TWh. Also the uses of wood chips and bark decrease (by 2.5 TWh and 0.3 TWh, respectively). The resulting feedstock shortage is covered up by an increase in the use of harvesting residues. A modest up and down in fossil fuel use can be observed. The price of fossil fuel is assumed to be constant across scenarios (since it is determined in global markets). For low levels of Bio-SNG production, the relative price of biomass versus fossil fuels increases. However, once the production of Bio-SNG reaches 15 TWh and beyond, the relative price of biomass-based feedstocks versus fossil fuels decrease due to an increased use of harvesting residues. For levels of Bio-SNG production higher than 15 TWh, harvesting residues are relatively cheaper compared to the increased price of wood chips, sawdust and pellets. The increased use of harvesting residues is possible due to increased roundwood harvest (see further below). As a result, the total amount of fossil fuel used is slightly lower in the 30 TWh Bio-SNG scenario compared to the baseline.

As a response to rising by-product prices, the incentive for sawnwood production increases (the by-product effect). A 26% increase in sawnwood production can be observed (Figure 6). At the same time, the industries using sawdust as input become less profitable (the competition effect). In the 30 TWh scenario, both the fiberboard and particleboard industries have ceased their production entirely due to the higher sawdust prices and the competition with the pellets industry. This model result is in line with the historical trend of an expanding HP sector using more and more bioenergy at the expensive of the board industry in Sweden (FAO Statistics, 2018; SFA, 2014).

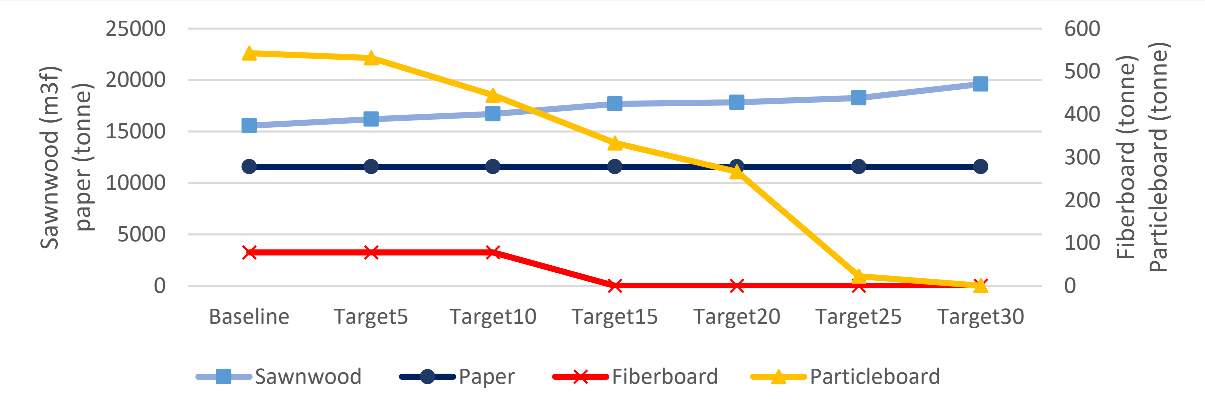

Figure 6: Final product production levels divided into four categories: Sawnwood includes three subgroups: spruce, pine and non-coniferous sawnwood (in m^3f). Paper includes three subgroups: newsprint, print paper and "other paper" (in tons). Sawnwood and paper production levels are shown on the left hand side axis. Fiberboard and Particleboard production levels are shown on the right hand side axis and are in tons.

With an increased sawnwood production, the demand for sawlogs increases and is met by an increase in the domestic sawlog harvest (see Figure 7). As a result, sawlog prices increase (Figure 8). For 30 TWh of Bio-SNG production, sawlog harvests increase by 8 million m^3f (27 %), reaching 39 million m^3f. As predicted by Di Fulvio, Forsell, Lindroos, Korosuo, and Gusti (2016), the price tends to increase exponentially with the quantity harvested. The price increase reaches 122 % for 30 TWh of Bio-SNG production. The lower domestic production of particleboard leads to a reduced demand for pulpwood, which in turn implies a 9% decrease in the domestic pulpwood prices (Figure 8). Moreover, with lower domestic pulpwood prices, exports of pulpwood increase and causes pulpwood harvest to grow by 7%, reaching 37 million m^3f (see Figure 7). With increased roundwood harvests, the supply of harvesting residues increase, and this explains the increased use of harvesting residues use in the HP sector (Figure 4).

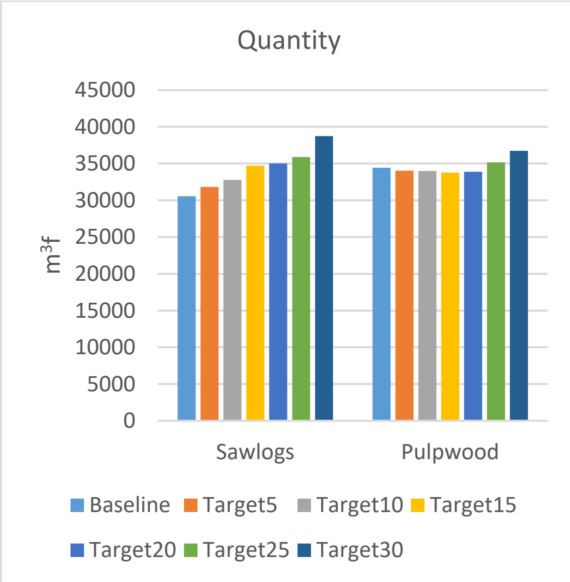

Figure 7: Harvest of sawlogs and pulpwood (spruce, pine and non conf. added together) in m^3f

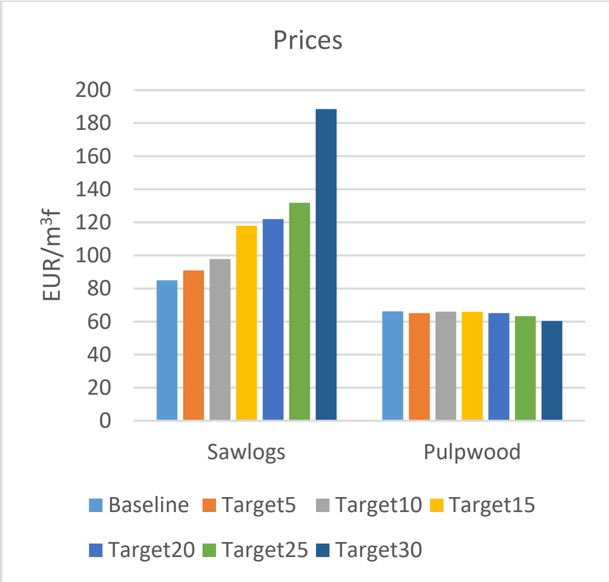

Figure 8: prices of sawlogs and pulpwood in EUR/m^3f.

Figure 9 shows that for 15 TWh of Bio-SNG production, the price of pulpwood falls below the price of wood chips. If pulpwood would have been allowed to be used as a feedstock in the HP sector, or in Bio-SNG production, a shift in the use of pulpwood would have been expected after 15 TWh. Thus, the waste hierarchy established by the EU is shown to be binding for 15 TWh of Bio-SNG production.

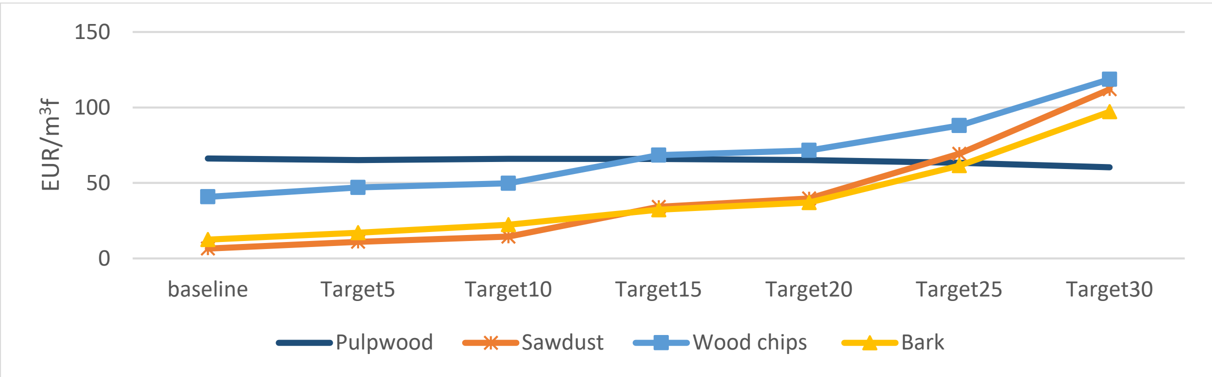

Figure 9: Price development of pulpwood and by-products (sawdust, wood chips and bark) m^3f.

To conclude, the prices of all by-products increase due to increased competition for the forest raw material, confirming that the HP sector becomes less profitable in the presence of increased 2G biofuel production. The competition for sawdust increases the most, and is re-allocated from the HP sector to Bio-SNG production. The HP sector is covering up the feedstock shortage with harvesting residues, which is made possible due to increased roundwood harvest (the by-product effect). Moreover, the fiberboard and particleboard industry eventually shut down due to higher input prices (the competition effect). The exit of fiberboard and particleboard production leads to increased pulpwood exports.

4.2. Sensitivity analysis: the role of imports

The simulation results presented in the previous sub-section implied a rise in domestic roundwood harvest, equivalent to almost a sixth of Sweden's harvest levels in the year 2016. However, future import levels for Sweden are uncertain, and will be determined by comparative advantages in biofuel production, policies and exports. In this section, imports are allowed to increase by 20% in relation to the levels observed in 2016. In this sensitivity analysis, we focus on the following feedstocks: forest industry by-products, pellets, sawlogs and pulpwood. The scenario results from section 4.1, i.e., assuming fixed imports levels corresponding to the 2016 levels, will be referred to as the "Base case". The scenario results in the sensitivity analysis, with an increased ceiling for possible import levels, are instead referred to as the "Higher import case". Several results are worth emphasizing.

First, the feedstock composition in Bio-SNG production does not change significantly; the main feedstocks are still sawdust and pellets. However, a larger proportion of the feedstock is imported in the Higher import case. The full import ceilings for industry by-products and pellets are reached already after 15 TWh of Bio-SNG production. For instance, with 15 TWh of Bio-SNG production, a total of 2.2 million m^3f domestically harvested sawlogs and associated harvesting residues, are replaced by 2.4 million m^3f of imported sawlogs. Since imported sawlogs generate no supply of harvesting residues, the imported amount of sawlogs has to be greater than the domestically amount of sawlogs that it replaces. Pulpwood imports, though, remain stable.

The by-product price developments in the Higher import case follow the same pattern as presented in the Base case. The price curve is shifted downwards, i.e., the increased imports delay the sharp price rises (see Figure 10). This is the expected result; the partial relaxation of the constraint on imports provides the industrial actors with more flexibility in procuring feedstock.

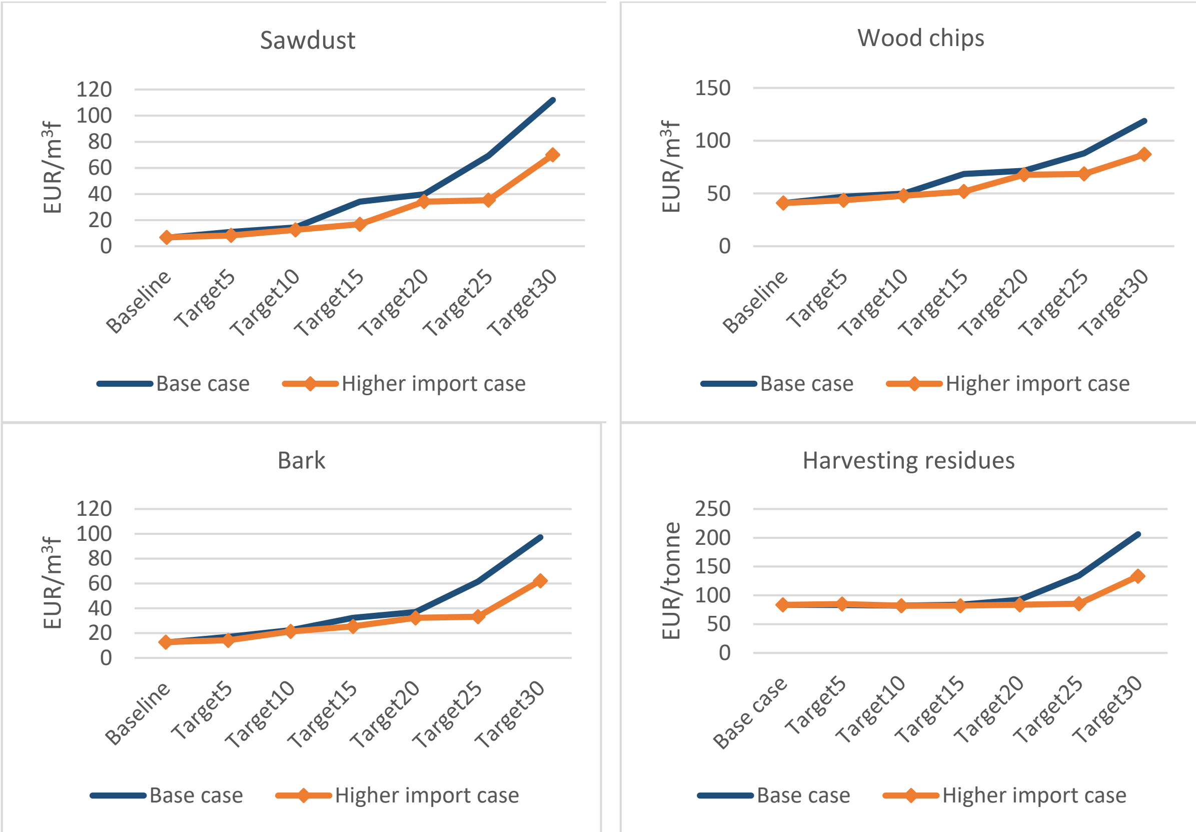

Figure 10: Price development for by-products and harvesting residues in the base case and in the Higher import case by-product is EUR/m³f and harvesting residues in tonne (ODT).

The relatively lower by-product prices cause the HP sector to use more by-products, domestically produced as well as imported, and less of harvesting residues (see Figure 11). Figure 10 indicates that the price of harvesting residues is also shifting downwards, similarly as in the case for the by-products. However, this change is not caused by an increased supply, supply is actually reduced due to decreased roundwood harvest. Instead, there is an decreased demand due to relatively cheaper by-products.

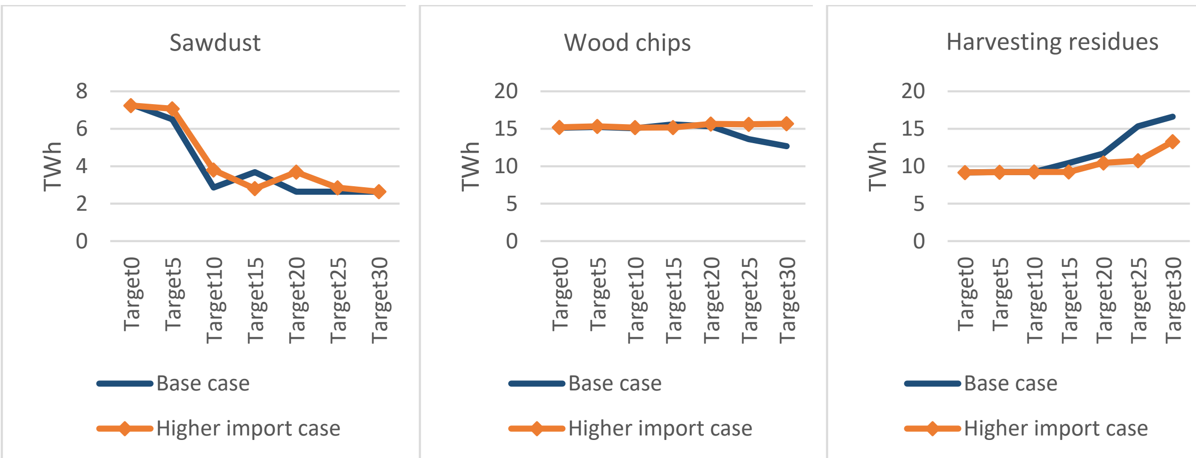

Figure 11 The use of sawdust, wood chips and harvesting residues in the HP energy sector (TWh).

The consequences of the increases in by-product prices in the Higher import case is also reflected in the forest industries' production levels (Figure 12). The production of fiberboard and particleboard, respectively, decreases and eventually both industries shut down. However, in the Higher import case, this shutdown is delayed; it takes place only when the production of Bio-SNG reaches 20 TWh (compared to 15 TWh in the base case). The production levels for sawnwood and paper are relatively stable due to direct substitution of imported raw materials for domestically harvested sawlogs and pulpwood. Since the board industry survives longer in the Higher import scenario, the domestic demand for pulpwood remains positive for higher levels of Bio-SNG production. Thus, the increase in pulpwood exports is lost and thus, pulpwood harvest is lower in the Higher import scenario.

Figure 12: Domestic forest industry production levels (in 1000 tonne) for 0-30 TWh Bio-SNG under the Base case and the More import case.

To conclude, regardless of whether import levels remain at 2016 levels, or increase by 20%, the general production patterns in the Swedish forest raw materials market will remain stable. Yet, a delay in events is expected; the increase in sawdust and harvesting residue prices are delayed, and so is the board industries' reduced production. Moreover, increased imports leads to lower harvest of roundwood as well as harvesting residues.

5. Discussion and analysis

This study demonstrates how feedstock competition in the Swedish forest biomass market is affected when implementing various 2G biofuel demand targets. It also demonstrates the linkages between the HP sector and forest industries; how these linkages can lead to both increased competition and industry shutdowns, but also synergy effects in the market for industry by-products. The simulated results are dependent on assumptions, such as which 2G biofuel technology is available, the available feedstocks, and model structure. This section provides a discussion of these issues and introduces ideas for future research avenues.

5.1. Modeling assumptions

The outcome of a partial equilibrium model is dependent on parameters, such as modeling assumptions, inputs and outputs included, and choice of technologies (Khabarov & Obersteiner, 2018; Rafajlovic & Cardwell, 2013; W. Thompson, S. Meyer, & T. Green, 2010; Whistance, 2012). This study has shown that with a 16% increase in domestic roundwood harvest, Sweden could produce up to 30 TWh of Bio-SNG without significantly reducing the share of biomass in the HP sector. The Swedish sawmill industry is found to be one of the winners due to the by-product effect, whereas the Swedish fiberboard and particleboard industries are found to be losers due to the increased competition for sawdust.

This result is in line with the findings by Trømborg et al. (2013), who assess the market effects of introducing 2G biofuels production in Norway; aggregate roundwood prices increase with increased 2G biofuel production. However, Trømborg et al. (2013) find raw material prices to increase significantly more than what is found in this study. Specifically, their results suggest that in the presence of a 4.5 TWh[11] increase in 2G biofuel production, the price of roundwood (pine in their case) increases by over 60%. In the present study, however, a similar increase in 2G biofuel demand generates a corresponding price increase of only 5%. 2G biofuel production has to be at least 30 TWh, before a 60% increase in the price of pine can be observed. These differences highlight the different prerequisites between countries in terms of existing production and resource endowments. For this reason, the feedstocks available to produce biofuel also differ between the models. Whereas our model incorporates by-products and harvesting residues, the model of Trømborg et al. (2013) defines pulpwood as the key feedstock,

[11] The authors do not specify which biofuel that is produced in the model. Assuming a biofuel for which one (1) liter is equal to 32.5 megajoule, 500 million liters biofuel equals 4.5 TWh.

something that also explains the sharp price increase reported for roundwood. Thus, the choice of feedstocks matters for the modeling outcomes. The same applies to the choice of technologies, which together with the feedstock constitutes the IO-coefficients. If, for instance, gasification of black liquor, an often underutilized by-product from the pulping industry, would be included and integrated with the pulp and paper sector, this industry would be a potential winner (Zetterholm et al., 2018).

5.2. Competition and by-product effects

The competition and the by-product effects are generally not separable and quantifiable since they occur simultaneously. Yet, and as indicated above, the course of events can be discussed in the light of these effects. All feedstock prices increase in the investigated scenarios, and two fiberboard industries eventually shut down, thus suggesting that the 2G biofuel demand targets lead to increased competition for the forest raw material. At the same time, though, there is also evidence of synergy effects between the sawmill sector and the use of forest raw material in the HP sector. Higher by-product prices spur sawmills to produce more sawnwood, something that in turn makes forest owners increase their harvest levels. Already in the 5 TWh Bio-SNG scenario, there is an increase in the harvest level, suggesting that the by-product effect kicks in from start. Moreover, in the 30 TWh Bio-SNG scenario, the average sawnwood price increases by a modest 0.9% due to increased returns on by-products.

In addition to forest industry by-products, harvesting residues use increases with more intense roundwood harvest activities, and this will have a mitigating effect on prices in the forest raw material market. More harvesting residues can be used in the HP sector, and this helps dampen some of the upward pressure on the price of industry by-products. This could in part explain the slowdown in the by-product price increase observed between 15 and 20 TWh of Bio-SNG production (Figure 3). The ups and downs in pellets and fossil fuel use, together with the increasing use of harvesting residues at 15 TWh of Bio-SNG production, suggest that the by-product effect intensifies at 15 TWh of Bio-SNG production. In the sensitivity analysis with increasing imports, the by-product effects are however reduced due to a decrease in domestically supplied harvesting residues.

Moreover, since this study has shown that the prices of by-products (sawdust, wood chips and bark) do influence the behavior of sawmills; sawdust, wood chips and bark, the feedstocks may better be described as co-products than by-products in the sawmilling sector. Thus, the demand for by-products influence the production of the main product – in this case sawnwood.

5.3. The potentials of harvesting residues

The quantities of feedstock available in the forest raw materials market are crucial for the price formation of feedstocks, and in the model, for which levels of 2G biofuels that will affect other sectors. Roundwood harvest, forest industry by-products and the demand for biomass are monitored by forest agencies or self-reported by industries. However, for harvest residues' availability and quantities harvested, no official data exist. Instead, researchers have to rely on techno-economic estimations and approximations. The supply of harvesting residues is constrained by the level of roundwood harvest. However the potential harvest of residues after felling is debated; in order to ensure environmental sustainability (avoid erosion, biodiversity losses etc.), some of the residues has to remain on the ground. De Jong, Akselsson, Egnell, Lofgren, and Olsson (2017) argue that an increase in the outtake of harvesting residues by 2.5 times current levels could be sustainable. However, others fear environmental backlashes for any harvest of residues on site since left-over biomass on the ground is important for the forest's biodiversity to recover after felling (e.g. Toivanen, Markkanen, Kotiaho, and Halme (2012). Porso, Hammar, Nilsson, and Hansson (2018) show that an increased pellets production using harvesting residues leads to carbon stock changes in soil and biomass, and this contributes to global warming. However, if coal in power plants can be replaced with pellets made from harvesting residues, an increased use of harvesting residues could instead contribute to mitigated climate change (Porso et al., 2018). Thus, there is no consensus on the optimal harvesting residues outtake level, yet the assumed harvesting residues supply levels are likely to affect the modeling outcomes for high levels of 2G biofuel production (when by-product prices approaches the price of harvesting residues per MWh produced 2GB).

The amount of available harvesting residues in the model is obtained from estimations by Carlsson (2011), which in turn build on techno-economic estimations of harvesting residue potentials. Recalling Figure 4, the price of harvesting residues becomes relatively lower to forest industry by-products at 15 TWh of Bio-SNG production. With lower or higher potential levels, the price could be higher respectively lower, and thus the intersection of relative prices at a different level of Bio-SNG production. For suggestions of future studies, an assessment of sustainable outtake of forest harvest residues could be combined with a market assessment of feedstock competition. For bioenergy HP conversion, compare the environmental effects from harvesting residues at roundwood harvest sites, with utilization of forest industry by-products, which may lead to increased roundwood harvest.

5.4. Model improvements

For future studies, the model could be further developed in terms of the time dimension, different 2G biofuel technologies, or ranges of feedstock inputs. Furthermore, by soft-linking the model to other models, e.g. techno-economic models, further aspects can be analyzed. A time dimension would make it possible to account for technological learning, and the analysis of feedstock prices and resource allocation over time for different biofuel scenarios. Technological learning following the increased penetration of 2G biofuel production could outweigh the initial price increases (Mustapha, Bolkesjø, et al., 2017).

More technologies in the model would open up for other feedstocks in 2G biofuel production, e.g., black liquor from the pulp- and paper industry. This way, more nuance could be added to the analysis regarding future winning and losing industries; could profitability in the pulp, and paper industry increase with the help of by-product demand, and thus lead to an increased comparative advantage internationally, and ultimately to more exports of paper products? Opening up to ranges (e.g., sawdust 50-100% and wood chips 50-100%) in the sets of IO-coefficients (technology and feedstock), could capture the various industries' substitution possibilities between feedstocks more accurately. This would be similar to the model GLOBIOM's handling of feedstock substitution in biodiesel production (Hugo Valin et al., 2013).

Finally, in order to analyze the spatial price dimension, the model could be soft-linked to techno-economic models (e.g. K. Pettersson et al. (2015). For instance, by linking to a spatially explicit localization model, geographic price aspects and the integration of biorefinery technologies with existing forest industries can be better incorporated in the analysis. By applying an iterative approach, feedstock price dynamics caused by biorefinery capacity enlargement can also be analyzed, as described by Bryngemark, Zetterholm, and Ahlström (2018).

Furthermore, the scenarios investigated in this study could be implemented in a different numerical model with the same data to compare the modeling approaches and perhaps different outcomes. Such comparison would contribute to a deeper understanding of the models' driving forces as well as pros and cons for specific research questions. A model to compare with could be a Constant Elasticity Model (CES), which would provide another way to deal with feedstock substitution as a CES model treats feedstock substitution explicitly and allows for continuously substitution (in contrast to indirect substitution in discrete steps).

6. Conclusions

The aim of this study was to analyze the price and resource allocation effects in the HP sector and forest industries from introducing domestic 2G biofuel production in Sweden. Six scenarios involving 5-30 TWh of Bio-SNG production were investigated. For this purpose, the national forest sector model SFSTMII model was extended with a module including 2G biofuel production.

All feedstock prices increased in the investigated scenarios, and two fiberboard industries were eventually shut down due to the increased price on sawdust. The results suggest that the 2G biofuel demand targets lead to increased competition in the forest raw material markets. Higher by-product prices spurred sawmills to produce more sawnwood, something that in turn made forest owners to increase harvest levels. Already in the 5 TWh Bio-SNG scenario, there was an increase in the roundwood harvest level, suggesting that the by-product effect kicked in from start. Moreover, in the 30 TWh Bio-SNG scenario, the average sawnwood price increased by a modest 0.9% due to increased returns on by-products.

With an additional roundwood harvest of 16% increase, Sweden could produce 30 TWh of 2G biofuels made from forest industry's by-product. In the case in which by-products and roundwood harvest imports could increase up to 20% in addition to 2016's imports levels, domestic harvest would have to increase by a little less (9%). However, if imports increase, less harvesting residues would be supplied and competition for by-products increase.

At a general level, this paper has highlighted the importance of considering price formation in forest biomass markets when developing bioenergy and 2G biofuel policies. Depending on the policy design, synergies may be achieved as well as increased competition for raw material leading to industrial shutdowns.

While the model presented in this paper offers a good starting point for analyzing the impact of 2G biofuel demand targets on a national forest raw material market, considering feedstocks from other sources (e.g., waste products in the agriculture sector) provides an important subject for future research. One possible solution would be to couple SFSTMII with an agricultural sector model to this model in order to consider substitution between other relevant sectors.

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Appendix: exogenous supply

Million m^3f	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
Region1				0,82	0,65	0,06
Region2				0,73	0,44	0,06
Region3				0,49	0,38	0,04
Region4			0,02	1,38	0,47	
ROW		6,19	7,37	14,88	14,19	-10,00

Table 2: Exogenous roundwood supply added to the data due to material imbalances in the calibration procedure. Column 2-4 show exogenous supply for sawlogs (spruce, pine and non-coniferous), and column 5-7 for pulpwood (spruce, pine and non-coniferous).

Million m^3f	Wood chips	Sawdust
Region1		
Region2		
Region3		
Region4		
ROW	94	115

Table 3: Exogenous supply of by-products added to the data due to material imbalances in the calibration procedure.