The Investments into Forest Biorefineries Under Different Policy Instruments

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Abstract

Increasing scarcity of oil reserves and the high CO_2 emissions from using oil have led to the development of renewable biofuels. This trend is intensified by the enactment of various energy policy measures. Biorefineries offer one important means to increase biofuel production. In the forest sector, biorefinery concept is especially interesting. For example, biofuel can be produced energy-efficiently in integrated pulp and paper mills due to synergy gains in production processes and raw material procurement. However, within the forest biorefinery platforms, there are number of raw-material, output mix and technology possibilities. This study analyzes, what policy instruments favor investments into each forest biorefinery type, and which types of paper and pulp mills are favorable for biofuel production. We present a market model of profit maximizing pulp and paper mills that allows investments into different biorefinery technologies. The model is utilized for numerical simulations, in which the impacts of three biofuel supporting subsidies on the biorefinery investments and raw-material choices are analyzed. The results show that the choice of the policy instrument affects not only the overall policy costs, but also the input use in biofuel production and the types of pulp and paper mills that are favorable for biofuel production.

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1 Introduction

The scarcity of oil and the CO_2 emissions related to its use have led to the development of alternative, renewable transportation fuels. Also, the energy policies of different countries and regions are pushing forward for this development. For example, European Union has decided that 10% of overall petrol and diesel consumption should be covered by sustainable biofuels by 2020 (EC 2008). Biorefineries offer one important solution for increasing biofuel production.

A general definition for a biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass. From an economic and market perspective, it is essentially a multiple input − multiple output production unit that uses renewable biomass in an efficient way. It has the flexibility to vary the raw-material choices and end products according to market conditions. In a pulp and paper mill integrated biorefinery, the biomass can be used for pulp, paper and energy production (electricity, heat, biofuels) as well as for chemicals (turpentine, acids, etc.). The forest or wood based biomass can be black liquor, pulpwood, chips, bark, sawdust or forest residues. Black liquor is a high-energy-content by-product of chemical pulp production, currently mainly combusted in recovery boilers to produce combined heat and power (CHP).[2]

Currently, there does not exist forest biorefineries integrated to pulp and paper mills. The biorefinery technology is to some extent new and has only recently advanced to the pilot or demonstration stage. Presently, a number of companies in North America and Europe are in process of making investments in full scale commercial biorefineries that are integrated to pulp and paper mills, and it is anticipated that they become operational within the next 2-4 years.

A number of factors are driving this development. First, the structural difficulties of forest industry in the traditional big forest sector countries, such as Canada, Finland, Sweden and the USA, have caused the industry to re-think its strategies. The forest industries in these countries have been suffering from continuous profitability problems for some time, as well as the ongoing, and related problem, of new investments increasingly going outside these countries (South-America, Asia). In

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[2] In the integrated pulp and paper mill, the heat is mainly used for drying pulp and paper, and for heating the mill. The power goes mainly to the turbines producing electricity. Heat may also be sold for district heating in urban areas close to the mill, and electricity can be sold to the grid.

this context, biorefineries are seen as one potentially important development which could enhance the profitability and viability of the existing mills.

Second, the climate and energy policies and the related energy price development are making investments to forest biorefineries increasingly attractive. Third, pulp and paper mills already have some of the required biorefinery infrastructure, e.g. wood raw-material procurement and processing capacity. Forest biorefineries can also utilize more efficiently the different wood raw-material and process side-stream fractions to produce multiple products, and hence take advantage of the synergy and scale effects of the production processes. Also, by producing multiple outputs, the capital and production costs can be allocated across the products, thus reducing the unit costs of each output. In short, biorefineries help to maximize the value derived from the biomass feedstock and existing infrastructure. As a result, products that may not be profitable to produce as a sole output could become market competitive when their production is integrated into simultaneous production of other products.

A pulp and paper biorefinery can use for example forest biomass, agricultural biomass, waste biomass or peat for biofuel production. Forest biomass, the focus of this study, has some clear advantages. For example, it does not compete with food or animal feed markets, to the extent that agricultural land is not converted to forest land. Also, forest biomass generally has better energy efficiency ratio than agriculture biomass. The other advantages include the year round availability, easy storing, high density that reduces shipping costs, low ash and sulfur content and well-developed infrastructure that exists for growth, harvesting, transportation and processing. In the existing investment plans to pulp and paper biorefineries, forest biomass is also the dominant raw material. On the other hand, energy is clearly the most important and dominant biorefinery output, at least in the coming decade. Chemicals play currently a minor role, although they may become more interesting in a longer term perspective and with the technology development.

In principle, almost any pulp and paper mill can become a forest biorefinery. However, within the forest biorefinery platforms, there are a number of different possibilities as regards to the choice of raw-materials, outputs and technology. Therefore, the number of investment opportunities and risk factors related to forest biorefinery are many. The viability of each specific forest biorefinery input-product-technology-mix depends on end markets (demand, supply, prices), substitute markets (e.g. oil), biomass markets, and on the global, national and regional policies. These may vary between countries, and within countries. Also, the policies to support biorefinery development depend on the goal that biorefineries are hoped to target. For example, depending on the degree that the policy goal emphasizes e.g. climate change mitigation, domestic energy self-sufficiency, rural employment, energy efficiency, forest residual use support or some combination of these, the optimal biorefinery concept may differ. In short, there is no single best uniform solution for forest biorefinery, rather a large number of different concepts, raw material options, production processes, and output mixes, each tailored to be optimal for the local conditions and objectives.

Because of the above, it is important to be able to analyze how different raw-material and energy price levels, as well as policy instruments impact the choice of forest biorefinery investments. For example, at what energy price and subsidy levels are forest biorefineries profitable? What type of raw-material basis, technology or end product-mix is most profitable? How do different policy measures change the prices and choices? However, given the very recent nature of the issue, it is no surprise that there does not appear to be any previous study or economic models that have analyzed these questions.

In this paper, we first formulate a model that describes profit maximizing pulp and paper mills and allows studying investments in different biorefinery technologies. In particular, the model allows analyzing technology and raw-material options in multi-output framework, in which the mill is producing biofuels as well as combined heat and power, along the conventional pulp and paper products. The model is applied to compute numerical simulations, in which we study the impacts of different policy instruments to technology and raw-material choices. That is, what kind of policy favors investments into each type of biorefinery technology and raw-material choice (forest and wood biomass, black liquor). Also, we study the effectiveness and costs of different biofuel supporting subsidies to find the cost-efficient instruments for different policy goals. The numerical simulations are based on plant level data from the Finnish pulp and paper industry and the Finnish energy markets. However, the model and the results can, to a significant degree, be generalized to other countries and markets where integrated pulp and paper mills are operating.

The policies analyzed in this study are an input subsidy for forest residue use in biofuel production, production subsidy for biofuel production and investment subsidy for a forest biorefinery.[3] The support for using forest residues has been raised as a possible policy option in many industrialized countries with substantial forest resources to promote collection of energy wood from costly forest

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[3] Forest residues are collected after final felling of a forest or within the improvement of young forest stands. They constitute of chipped logging residues, small-sized trees, stumps and roots.

sites, and to reduce the input transportation costs of companies using energy wood. Production subsidy increases the profitability of biofuel production. Investment subsidies aim at speeding up the initialization of biofuel technologies and thus create a foundation for continued biofuel production.

The studied biorefinery types produce crude biofuels, which can then be refined to biofuel (e.g. diesel) in a separate refinery. The crude biofuels are assumed to be produced from synthesis gas (syngas).[4] The biorefinery can produce syngas in three different ways: black liquor gasification, wood biomass gasification or the gasification of both. The mill can thus invest in black liquor or other biomass gasifier and use the biomass for biofuel production. However, in the case of the black liquor gasifier, the mill loses the black liquor based process energy, which the mill requires for the pulp and paper making. Therefore, this “lost energy” has to be compensated by using additional biomass or other fuels for producing energy for the pulp and paper processes. Thus, there is a trade-off between the amount of biomass used for pulp and paper production and energy production. Given a fixed amount of pulp production of the mill, the more energy is produced in the mill, the more biomass is needed. On the other hand, there is a trade-off between pulp and energy production. Given a fixed amount of biomass, the more energy is produced, the less pulp can be produced.

The black liquor gasification process is mainly developed in Sweden (Chemrec 2009). The other option, and currently more popular one, is to invest in forest biomass gasification. In this case, the mill uses bark, forest residues, pulpwood, or chips for the gasifier (instead of black liquor), and produces liquid biofuels (and electricity and heat). In this case, the black liquor of the pulp process is used to CHP production in a recovery boiler, as is done currently. This concept is being developed intensively e.g. by the Finnish companies. The companies have announced that they will invest in the near future to a pulp and paper mill integrated biorefinery in Finland or other European country (France, Sweden and Estonia have been mentioned as alternative locations). The third option is to invest both in black liquor and wood residual gasifier and use the produced syngases to liquid biofuel production and CHP production in a gas turbine. This option is being considered for example in the USA (Larson et al. 2006). In the two latter options, the produced amount of biofuels is not strictly restricted by the pulp production decision.

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[4] We restrict the analysis to gasification processes, and therefore do not consider biochemical processes, such as fermentation. Currently, the gasification technology has advanced more rapidly and extensively to actual investment stage, especially in the Nordic Countries.

So far the research on biorefineries has been technology driven and specialized (Larson et al. 2006, McKeough, Kurkela 2008). This is natural, since the advancements in technology are recent, and the possibilities of moving this technology into practice are only opening. Now that the technology is close to its commercial stage, there is a clear need for synthesis of the current knowledge, and analytical assessment of future economic and policy prospects. However, the literature and knowledge on these issues is very limited. Although there are a number of studies that have constructed pulp and paper sector models (Buongiorno et al. 2003, Szabó et al. 2009), there appears to be no numerical simulation (or econometric) model that incorporates biorefineries into the pulp and paper sector. At a conceptual and analytical level, Söderholm and Lundmark (2009) consider the economic implications of biorefineries integrated with pulp and paper mills. However, they do not construct formal model, and they restrict their analysis purely to black liquor gasification process. Thus, none of the previous studies link the pulp and paper markets with the investment possibilities for different biorefinery technologies.

The present study contributes to the literature by formulating a partial equilibrium pulp and paper market model that explicitly incorporates the biorefinery investment opportunities to the model. The model is also used for numerical simulations, in which we analyze the impact of different price levels and policies to biorefinery investment decisions, particularly to the raw-material and technology choices.

2 The model

The partial equilibrium market model describes plants that produce pulp, paper, biofuel, and combined heat and power (CHP). The model has different types of producers (plants), depending on the input-output mix and technology choices. The plants can differ with respect to the raw-material inputs, pulp and paper grades produced, and the production technology used to produce biofuel and CHP. The initial production capacities of the plants are determined by the plant type. The plants can invest in biorefinery and CHP capacity. The paper, pulp, heat, biofuel and wood markets are cleared in the model, i.e. the respective prices are endogenous. Thee model does not allow investments in new pulp and paper capacity, because the problem is static, and the focus is on biofuel capacity investments. This assumption can be regarded as an approximation of the current situation in Canada, Finland, Sweden and the USA. These countries have been, and still are, suffering from the overcapacity of pulp and paper production. In the horizon, there is no new significant investments in increasing pulp and paper capacity in these countries, on the contrary, there is likely to be further capacity reductions.

2.1 Modeling production technology

We use a multi-output, multi-input model to describe the optimal management of the pulp and paper mill. The separate production functions are formulated for all the production processes that yield pulp, paper, biofuel, and CHP. The model allows for different grade groups for paper and pulp (e.g. fine paper and newsprint, and chemical and mechanical pulp). Firm can invest in biorefinery capacity, which allows treating the plant as a forest biorefinery integrate. The initial biofuel production capacity for all the producers is assumed to be zero, i.e., if the mill does not invest on biofuel production, the biofuel production possibilities are neglected. The firm maximizes profits, given input costs and output prices in competitive markets.

The individual production processes of pulp, paper and biofuel from an input are described by Leontief –type production functions, i.e. inputs are used in fixed proportions per output unit. However, since pulp and paper outputs with the same properties can be produced from several inputs, in pulp and paper production the Leontief functions are nested in a perfect substitute production function. The CHP production differs from the other production processes. There, we follow Kangas et al. (2009) and Lintunen and Kangas (2010) and specify a linear function of energy transformation in combustion. The linear function is augmented with convex co-firing costs when appropriate. For the wood inputs we specify convex costs. Thus, the model allows non-constant returns to scale.

There are many possible production technologies in the integrated mill. First, paper grades can be produced using different combinations of inputs. In paper production, the mill optimizes the production level for each paper grade. Second, pulp can be produced from different inputs, e.g. from pulpwood or recycled paper. The production of chemical pulp also yields considerable amounts of black liquor as a by-product. In pulp production, the mill optimizes the wood input and recycled paper input usage. The firms can use pulp either for paper production or sell it to markets. In accordance, it is possible for the mill to buy market pulp, or use pulp produced in the integrate.

Biofuel production is based on black liquor or on different types of timber and forest biomass (i.e. pulpwood, bark, chips, sawdust, forest residues), along with other inputs. The biofuel production process generates by-product gases that can be used for heat and power production. In biofuel production, the firm optimizes the biomass input use (forest and wood biomass types and black liquor). The firm can invest in separate biofuel capacities based on black liquor or forest biomass inputs.

In addition, the mill produces heat and electricity. The model allows for several production technologies with associated fuel inputs. In heat and electricity production, the mill optimizes the fuel use (e.g. black liquor or natural gas). Since the biofuel production alters the energy balance and the black liquor and wood input use in a pulp and paper integrate, the investments in CHP capacity are made possible in the model. The wood and forest biomass material flows of a forest biorefinery integrate are presented in Figure 1.

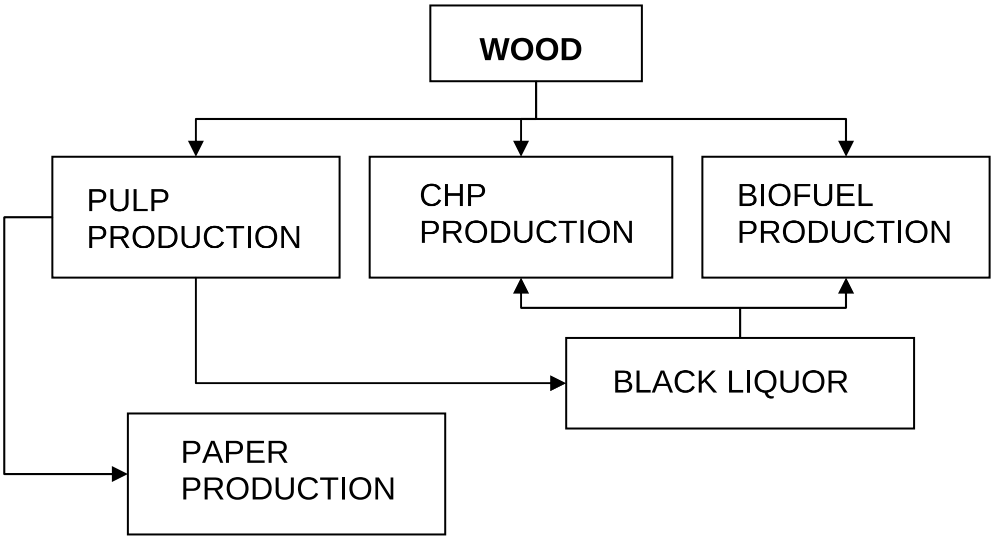

Figure 1. The wood material flows in an integrated forest biorefinery.

2.1.1 Paper production

Each paper grade is produced by pulp, energy and other inputs.[5] Production function for paper grade $m \in PA$ is

$$y^m = \min\left\{\frac{x_g^m}{a_g^m}, \frac{x_j^m}{a_j^m}, \ldots, \frac{x_l^m}{a_l^m}\right\}. \tag{1}$$

The parameters, *a*, are constant input requirements for production of a unit of output. The pulp grades inputs are denoted by $g \in PG$ and the energy inputs $j \in J = \{electricity, heat\}$. The labor inputs are denoted by *l*. In the model, we separate the pulp costs from the other costs. The procedure is based on known result that in cost minimum, $y = x_i / a_i$ for all inputs *i*. The costs based on input

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[5] The other inputs include chemicals, which are a notable cost factor in paper production.

use, x_i, given input prices, p_i, are obviously $c = \sum_{i \in I} p_i x_i$ .Therefore, we can write semi-net revenues (excluding pulp costs) from paper production as

$$R^m = p_m y^m - c(y^m) = \left(p_m - \sum_{i \in I_m} p_i a_i^m \right) y^m , \tag{2}$$

where the set I_m contains all the non-pulp inputs. Given the production levels, y^m, of paper grade, $m \in PA$, the consumption of pulp in the manufacturing of paper is

$$x_g = \sum_{m \in PA} a_g^m y^m . \tag{3}$$

This consumption condition is a production level requirement for the pulp production.

2.1.2 Pulp production

Production function for pulp process is based on assumption that several wood inputs can be used to produce a given pulp grade. However, with different wood inputs, distinct proportions of other inputs are needed in the process. We specify separate Leontief-type functions for all the wood inputs and consider the outputs identical. Therefore, the production function for different pulp grades $g \in PG$ is presented as a nested perfect substitute function

$$y^g = \sum_{w \in WT} y_w^g = \sum_{w \in WT} \min \left\{ \alpha_w^g z_w^g, \frac{x_{jw}^g}{a_{jw}^g}, \dots, \frac{x_{lw}^g}{a_{lw}^g} \right\} . \tag{4}$$

The model contains several wood fiber categories, $w \in WT$. In order to make the notation clearer in later stages, we have handled wood inputs differently from the other inputs. The constant coefficient α denotes the amount of output produced by unit input, i.e. it is an inverse of the other coefficients a. As we formulate the profit maximization problem for wood fiber inputs, the other inputs are set to be used at their cost minimizing level. We follow the procedure presented in previous subsection but extend it slightly: Here we base the costs not on output but wood inputs. With Leontief function, the cost minimizing level of input use is $y_w = x_{iw} / a_{iw}$ for all non-wood inputs *i* and $y_w = \alpha_w z_w$ for wood inputs. Using these optimal conditions with the non-wood input cost relation $c = \sum_{i \in I} p_i x_i$ one ends up with non-wood input cost function as a function of wood use

$$c^g(\mathbf{z}^g) = \sum_{w \in WT} c(z_w^g) = \sum_{w \in WT} \alpha_w^g z_w^g \sum_{i \in I_g} p_i a_{iw}^g . \tag{5}$$

2.1.3 Biofuel production

The biofuel production is the combined production of crude fuel from black liquor (*bl*) and from wood fibers ($w \in WT$). Separate gasifiers are needed for black liquor and wood fibers. However, the same procedure as in the case of pulp production is applicable here. The biofuel production function is

$$y^{bf} = \sum_{b\in GI} \min\left\{ \alpha_b^{bf} z_b^{bf}, \frac{x_{j,b}^{bf}}{a_{j,b}^{b}}, \dots, \frac{x_{l,b}^{bf}}{a_{l,b}^{bf}} \right\}, \tag{6}$$

where *bf* refers to biofuel and $b \in GI = \{bl\} \cap WT$ denotes the inputs and the semi-net profits (excluding wood fiber costs) from biofuel production are

$$\begin{aligned} R^{bf} &= p^{bf} \sum_{b\in GI} \alpha_b^{bf} z_b^{bf} - \sum_{b\in GI} \alpha_b^{bf} z_b^{bf} \sum_{i\in I_{bf}} p_i a_{i,b}^{bf} \\ &= p^{bf}\left(\alpha_{bl}^{bf} z_{bl}^{bf} + \sum_{w\in WT} \alpha_w^{bf} z_w^{bf} \right) - \alpha_{bl}^{bf} z_{bl}^{bf} \sum_{i\in I_{bf}} p_i a_{i,bl}^{bf} - \sum_{w\in WT} \alpha_w^{bf} z_w^{bf} \sum_{i\in I_{bf}} p_i a_{i,w}^{bf} . \end{aligned} \tag{7}$$

The production of biofuel yields gas as a by-product (McKeough, Kurkela 2008)

$$x_d = \gamma_d y^{bf}, \tag{8}$$

where γ_d is the share of by-product gas that is generated by producing one unit of biofuel.[6] The by-product gas can be used as a fuel in CHP production.

Since in biofuel production black liquor and wood fibers need different gasification technologies, these processes differ in terms of capital requirement. Thus, separate investment decisions for the biofuel production have to be formulated for both fuel types. Initially, there is no biofuel production capacity in any of the plant types. We assume that the marginal biorefinery investment cost decrease as the size of an investment increases. The scale economies induce concave costs. The specification follows that of Mäkelä et al.(2010). The unit cost of invested capacity, c_{inv}, is set at a given reference level of capacity χ_{calib}. Around this reference level, the investment costs vary with elasticity of $\omega_I < 1$ indicating concave costs. Altogether, the investment costs are defined as

$$C_{inv,b}^{bf} = c_{inv,b}^{bf} I_b^{bf} \left(\frac{I_b^{bf}}{\chi_{calib,b}^{bf}} \right)^{\left(\omega_{I,b}^{bf} - 1\right)}, \tag{9}$$

for both technologies $b \in GT = \{BL, WOOD\}$.

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[6] The biorefineries can, to some extent, vary the ratio of produced biofuel and by-product gas, but we have not taken that into account, since there is no valid data available.

2.1.4 CHP production

For CHP generation, we employ a linear energy conversion process, i.e. the power plant has constant output efficiency η_j given any fuel input mix. This means that in energy transformation the fuels are perfect substitutes. In the case of co-firing there are convex costs that cause the fuels to have a variable degree of substitutability. The net revenues of heat and power co-generation are presented by

$$R^{chp} = \sum_{s\in BT} R_s^{chp} = \sum_{s\in BT}\left(\sum_{j\in J} p_j \eta_{j,s} \sum_{f\in F_s} x_{f,s} - c_{f,s}(x_s) - \sum_{f\in F_s} p^{ec}\varepsilon_f x_{f,s}\right), \tag{10}$$

where $j \in J = \{el, heat\}$ are the outputs and $s \in BT$ are the boiler types. Each boiler type has a set of allowed fuels, $f \in F_s$. The emission trading costs are determined by the price of emission credit p^{ec} and the emission factor of the fuel ε_f. The detailed descriptions of the CHP cost functions $c(x_s)$ for different boiler types and fuels are given in the Appendix A. Investments are also possible to new CHP capacity. The investments are modeled in the same manner as for biorefineries and the investments are boiler type specific.

2.1.5 Plant level profit maximization

In the formulation of the production functions, the wood fiber input costs were omitted. We model these costs through purchased wood fiber inputs z_w^B for all the wood fiber categories $w \in WT$. The convex wood fiber input costs can be expressed as

$$\sum_{w\in WT} c^w\left(z_w^B\right) = \sum_{w\in WT} p_w z_w^B + \frac{2}{3}\sum_{w\in WT} t_w z_w^{B^{\frac{3}{2}}}, \tag{11}$$

where *B* refers to buying, p_w is the price of wood fiber type *w*, and t_w is a unit transport cost that increases as a square root of fuel use. It is assumed that transport costs grow linearly with the distance of fuel delivery and that the fuel sources are evenly scattered. Therefore, the parameter value 3/2 is based on geometry (Kangas, Lintunen & Uusivuori 2009).

In case of market pulp, the mill sells it at given market price, which generates the following revenue function

$$R^p = (p_p - c_p^S)x_p^S, \tag{12}$$

where *S* refers to selling, c_P^S are the extra costs linked to pulp selling (i.e. drying the pulp and transportation) and x_p^S is the amount of sold pulp.

Given the above specifications and assumptions, the pulp and paper plant's profit maximization function can be expressed as

$$\max_{\{\boldsymbol{y},\boldsymbol{z},\boldsymbol{x},\boldsymbol{I}\}} \pi\left(\boldsymbol{y},\boldsymbol{z},\boldsymbol{x},\boldsymbol{I}\right)=\sum_{m\in PA}\left(p_m-\sum_{i\in I_m}p_i a_i^m\right)y^m+\sum_{g\in PG}\left(p_g-c_g^S\right)x_g^S-\sum_{w\in WT_g}\alpha_w^p z_w^p\sum_{i\in I_g}p_i a_{iw}^p$$
$$+p^{bf}\sum_{b\in GI}\alpha_b^{bf}z_b^{bf}-\sum_{b\in GI}\alpha_b^{bf}z_b^{bf}\sum_{i\in I_{bf}}p_i a_{ib}^{bf}+\sum_{s\in BT}\left(\sum_{j\in J}p_j\eta_{js}\sum_{f\in F_s}x_{fs}-c_{fs}(\sum_{f\in F_s}x_{fs})-\sum_{f\in F_s}p^{ec}\varepsilon_f x_{fs}\right). \tag{13}$$
$$-\sum_{w\in WT}\left(p_w z_w^B+\frac{2}{3}t_w\left(z_w^B\right)^{\frac{3}{2}}\right)-\sum_{b\in GT}c_{inv,b}^{bf}I_b^{bf}\left(\frac{I_b^{bf}}{\chi_{calib,b}^{bf}}\right)^{(\omega_{I,b}^{bf}-1)}-\sum_{s\in BT}c_{inv,s}^{chp}I_s^{chp}\left(\frac{I_s^{chp}}{\chi_{calib,s}^{chp}}\right)^{(\omega_{I,s}^{chp}-1)}$$

There are several constraints in the pulp and paper plant's profit maximization problem. First, there are feasibility constraints for wood fiber, pulp, black liquor, by-product gas and heat. Wood fiber used for pulp, biofuel and CHP can not exceed the amount of wood fiber purchased, i.e.:

$$z_w^B-\sum_{p\in PU}z_w^p-z_w^{bf}-z_w^{chp}\geq 0, \tag{14}$$

for all $w\in WT$. The amount of pulp used for paper production and sold as market pulp, can not exceed the amount of pulp produced and purchased:

$$\sum_{w\in WT}\alpha_w^p z_w^p+x_g^B-a_g^m y^m-x_g^S\geq 0. \tag{15}$$

Black liquor used for biofuel and CHP can not exceed the amount of black liquor generated as a by-product of pulp production:

$$\beta_{bl}^p\sum_{w\in WT_P}\alpha_w^p z_w^p-z_{bl}^{bf}-x_{bl}^{chp}\geq 0, \tag{16}$$

where β_{bl}^p is the share of black liquor generated as a by-product from producing one unit of pulp. The use of biorefinery by-product gas in CHP production can not exceed the amount of gas that is generated from the biofuel production:

$$\gamma_g\sum_{b\in GT}\alpha_b^{bf}z_b^{bf}-x_g^{chp}\geq 0. \tag{17}$$

All the heat that is used in the pulp and paper production processes and sold to the markets must be produced in the CHP processes:

$$\sum_{s\in BT}\eta_{heat,s}\sum_{f\in F_s}x_{f,s}-\sum_{m\in PA}a_{heat}^m y^m-\sum_{p\in PG}\sum_{w\in WT}\alpha_w^p z_w^p a_{heat,w}^p-y_{heat}^s\geq 0. \tag{18}$$

Finally, there are capacity constraints for production of paper, pulp, biofuel from wood fiber, biofuel from black liquor and CHP production, respectively:

$$y_{\max}^{m} - y^{m} \geq 0 \tag{19a}$$

$$y_{\max}^{p} - \sum_{w \in WT} \alpha_{w} z_{w}^{p} \geq 0 \tag{19b}$$

$$I_{bl}^{b} - \alpha_{bl}^{b} z_{bl}^{b} \geq 0 \tag{19c}$$

$$I_{wood}^{b} - \sum_{w \in WT} \alpha_{w}^{b} z_{w}^{b} \geq 0 \tag{19d}$$

$$x_{\max,s}^{chp} + I_{s}^{chp} - \sum_{f \in F_s} x_{fs} \geq 0, \tag{19e}$$

where $y_{\max}$ and $x_{\max}$ refer to initial production and fuel input capacities, respectively. Denoting the constraints of the optimization problems by $w_f \geq 0$ where f belongs to the set of constraints of the problem (PC), the Lagrangian of the problem is given by

$$L = \pi + \sum_{f \in PC} w_f \lambda_f , \tag{20}$$

where λ_f is the Lagrangian multiplier, i.e. the shadow price of the constraint.

2.2 Demand and market equilibrium

The exogenous part of the demand is specified with a constant elasticity formulation. However, there are also endogenous parts in the demand. The demand functions for different paper (*m*) and pulp (*p*) grades and wood fiber types *w* are, respectively:

$$D^{m} = d_{m}^{0} \left(\frac{p_{m}^{0}}{p^{m}} \right)^{\varepsilon_m} \tag{21a}$$

$$D^{p} = d_{p}^{0} \left(\frac{p_{p}^{0}}{p^{p}} \right)^{\varepsilon_p} + \sum_{k} x_{pk}^{s} \tag{21b}$$

$$D^{w} = \sum_{k} z_{wk}^{B} , \tag{21c}$$

where d^0 and p^0 are the reference demand and price, respectively, ε is the elasticity and *k* refers to the producers. Heat demand is modeled similarly with the paper demand.

The supply of a paper grade *m* is the aggregated production of paper grade *m* by all the producers and the supply of pulp grade *g* is the aggregated amount sold by all the producers. Heat supply is the sum of sold heat by all the producers. The supply for wood fiber is specified as

$$S_{w} = s_{w}^{0} \left(\frac{p_{w}}{p_{w}^{0}} \right)^{\varepsilon_w} . \tag{22}$$

The pulp, paper, biofuel, heat and wood markets are cleared in the model. The output prices are solved from the market clearance condition for market *K*:

$$S_K \geq D_K \,. \tag{23}$$

2.3 Policy instruments

We study three policies to increase the biofuel production: production subsidy, input subsidy and investment subsidy. The production subsidy is a price premium on top of the fuel price for all the biofuel units produced. The input subsidy is received for each unit of a wood fiber type used in biofuel production. The input subsidy may be wood fiber type specific and in the numerical simulation we apply input subsidy for forest residue use in biofuel production. The investment subsidy is a share of investment costs that is paid by the government.

The semi-net profits from biofuel production in the case of production subsidy (s^{pr}) are:

$$R^{bf} = \left(p^{bf} + s^{pr}\right)\left(\alpha_{bl}^{bf} z_{bl}^{bf} + \sum_{w \in WT} \alpha_w^{bf} z_w^{bf}\right) - \alpha_{bl}^{bf} z_{bl}^{bf} \sum_{i \in I_{bf}} p_i a_{i,bl}^{bf} - \sum_{w \in WT} \alpha_w^{bf} z_w^{bf} \sum_{i \in I_{bf}} p_i a_{i,w}^{bf} \quad . \tag{24}$$

The corresponding semi-net profits in the case of input subsidy (s^{ip}) are:

$$R^{bf} = p^{bf}\left(\alpha_{bl}^{bf} z_{bl}^{bf} + \sum_{w \in WT} \alpha_w^{bf} z_w^{bf}\right) - \alpha_{bl}^{bf} z_{bl}^{bf} \sum_{i \in I_{bf}} p_i a_{i,bl}^{bf} - \sum_{w \in WT} \alpha_w^{bf} z_w^{bf} \sum_{i \in I_{bf}} p_i a_{i,w}^{bf} + s^{ip} z_w^{bf} \,. \tag{25}$$

Investment subsidy, $s^{inv} = \left[0,1\right]$, is a share of investment costs:

$$C_{inv,b}^{bf} = (1 - s^{inv}) c_{inv,b}^{bf} I_b^{bf} \left(\frac{I_b^{bf}}{\chi_{calib,b}^{bf}}\right)^{(\omega_{I,b}^{bf} - 1)\sigma_b^{bf}} \quad . \tag{26}$$

3 Policy impacts: Numerical application

The model presented in Chapter 2 is applied to analyze the levels of crude oil price and policy instruments that are needed to reach biofuel production targets. A competitive market partial equilibrium model is formulated as a mixed complementarity problem and the optimization problem is solved using PATH solver in GAMS modeling system. The setting is based on real plant level data from pulp and paper industry and the energy market in Finland in 2008 (the data is given in the Appendix B). Biofuel is assumed to be a perfect substitute to crude oil. There are currently no forest biorefineries in Finland, so the initial biofuel production level is set to zero.

3.1 Model features

The model has four paper grades, three pulp grades and six wood fiber types. Chemical pulp is the only pulp grade that is traded in the markets; hence it solely constitutes the market pulp category.

Recycled paper is treated as one wood fiber type in the model. The paper and pulp grades and wood fiber types are presented in Table 1.

Table 1. The paper and pulp grades and wood fiber types.

Grades/types						
Paper grades	Newsprint	Finepaper	Magazinepaper	Paperboard		
Pulp grades	Mechanical	Chemical	Recycled			
Wood fiber types	Pulpwood	Chips	Sawndust	Bark	Forest residues	Recycled paper

There are five different boiler types for CHP production in the model: recovery boiler, fluidized bed boiler, gas turbine, oil boiler and heat boiler. Table 2 presents the allowed fuels for the different boiler types.

Table 2. The allowed fuels for different boiler types.

Boilers and fuels	*Allowed fuels:*	
Recovery boiler	Black liquor	
Fluidized bed boiler	Wood fiber*	Peat
Gas turbine	Natural gas	By-production gas
Oil boiler	Oil	
Heat boiler	Wood fiber*	

*The fuel wood fiber contains all wood fiber types except recycled paper.

The initial capacities for paper, pulp and CHP production are determined by the plant type. The pulp and paper industry structure is given by the Finnish market structure, and it consists of the following plants:

- *Finepaper* producers (9 units)
- *Paperboard* producers (6 units)
- *Magazinepaper* producers (4 units)
- Stand-alone *pulp* producers (3 units)
- *Fine-* and *magazinepaper* producers (2 units)
- *Newsprint* producer (1 unit)
- *Finepaper* and *paperboard* producer (1 unit)
- *Newsprint* and *paperboard* producer (1 unit)
- *Newsprint* and *finepaper* producer (1 unit)
- *Magazinepaper* and *paperboard* producer (1 unit)
- *Newsprint* and *magazinepaper* and *paperboard* producer (1 unit)

3.2 Results

The results are calculated for three biofuel supporting policy cases: *production subsidy*, *input subsidy* for forest residue use and *investment subsidy*. To make the policy cases comparable, we analyze all the cases in a situation, where biofuel demand (or policy target) is fixed on a level 2500 GWh per year. This is around 5 % of the Finnish transportation fuel use. The required subsidy levels are calculated endogenously for fuel prices ranging from 0 to 80 €/MWh (or 0 to 200 $/barrel). The 2008 average crude oil price was 36.5 €/MWh (or 91 $/barrel).

The production and input subsidy values and investment subsidy shares for 0-80 €/MWh fuel prices and 2500 GWh biofuel production target are presented in Figure 2. The required production subsidy values are between 0 and 77 €/MWh biofuel production. For the 2008 reference crude oil price, the production subsidy level is about 40 €/MWh. The input subsidy values range from 0 to 53 €/MWh forest residual use. With the 2008 crude oil price, the required input subsidy level is about 30 €/MWh forest residual input use. The investment subsidy only works in quite a narrow range of fuel prices. Therefore, there are no values for investment subsidies for fuel prices under 63 €/MWh.[7] With lower fuel prices, the required investment subsidy share would be over 100 %. This is due to the high production costs compared to the fuel price.

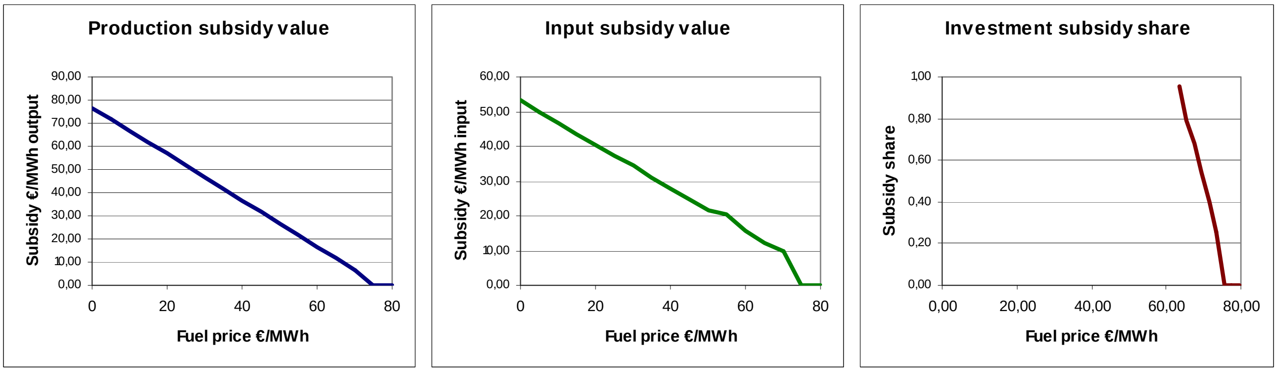

Figure 2. The required production and input subsidy values and investment subsidy share, when biofuel production target is 2500 GWh per year.

Figure 3 indicates the total subsidy costs for all the examined subsidies. The investment subsidy is inefficient compared to the other two subsidies. That is because investment subsidy does not support the production decision and production is too expensive compared to the fuel price.

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[7] The investment subsidy share is not 100 % for any fuel price in Figure 2. That is because the GAMS-program had difficulties to find the optimal solution, when the required investment subsidy share approaches 1. However, it can be noted that the price, when the required investment subsidy share is 100 %, is slightly under 63 €/MWh.

However, input subsidy lowers the biofuel production costs and production subsidy increases the profitability of biofuel production, so they work more efficiently than investment subsidy. The total policy costs are slightly lower for production subsidy than for input subsidy.

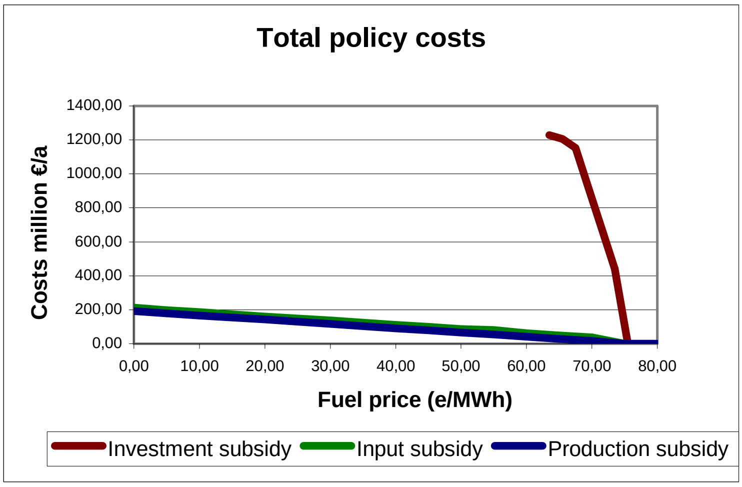

Figure 3. Total policy costs for the three subsidies.

The results are run for multiple fuel (e.g. crude oil) prices and it seems obvious that the fuel price has an impact on the results: the higher the fuel price, the lower the subsidy values and total policy costs. However, it seems that to attain the 2500 GWh biofuel policy target, the subsidies are vital. Only for extremely high fuel prices, the subsidies are not needed.

Figure 4 shows the share of wood as an input in biofuel production and the forest residual use in biofuel production.[8] In the case of input subsidy, biofuel production is solely based on forest residues, if the fuel price is under 70 €/MWh. With very high fuel prices, also other inputs are used. In the cases of production and investment subsidy, forest residues, but also other wood fiber (bark) and black liquor are used as inputs in biofuel production.

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[8] Naturally, the share of black liquor use in biofuel production is one minus the wood share.

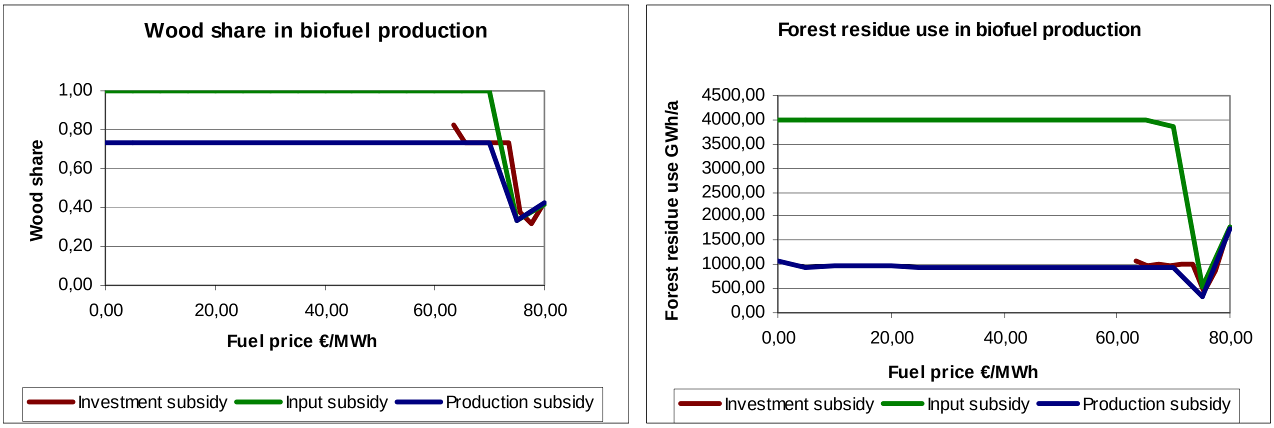

Figure 4. Wood share in biofuel production .

Figure 5 indicates the distribution of the investments into different pulp and paper plant types in the cases of input subsidy and production subsidy. The investments are showed for fuel prices between 20 and 50 €/MWh (or 50 and 125 $/barrel). In the case of investment subsidy, there are no investments in this price range. All the plants investing in biorefineries have gas boiler capacity, with both policies. In biofuel production, gas is obtained as a by-product. Thus the plants having gas boilers can utilize this non-marketable gas without investment costs. The size of wood/black liquor gasifier is similar in all mills investing, as the returns are close to each other due to similar technologies. According to the results, the optimal size of the wood gasifier would be approximately 36 MW, while for black liquor gasifier the optimal size would be 75 MW. The optimal size is affected on the other hand by decreasing marginal investment cost and on the other hand by increasing marginal wood use cost.

As can be noted from the results, the choice of policy instrument impacts also the distribution of biorefineries into different pulp and paper mill types. The input choice also affects the investment choice, because wood fiber inputs and black liquor inputs require separate capacity in biofuel production. Investments into black liquor based biorefineries were only made in the case of production subsidy and by the finepaper producers.

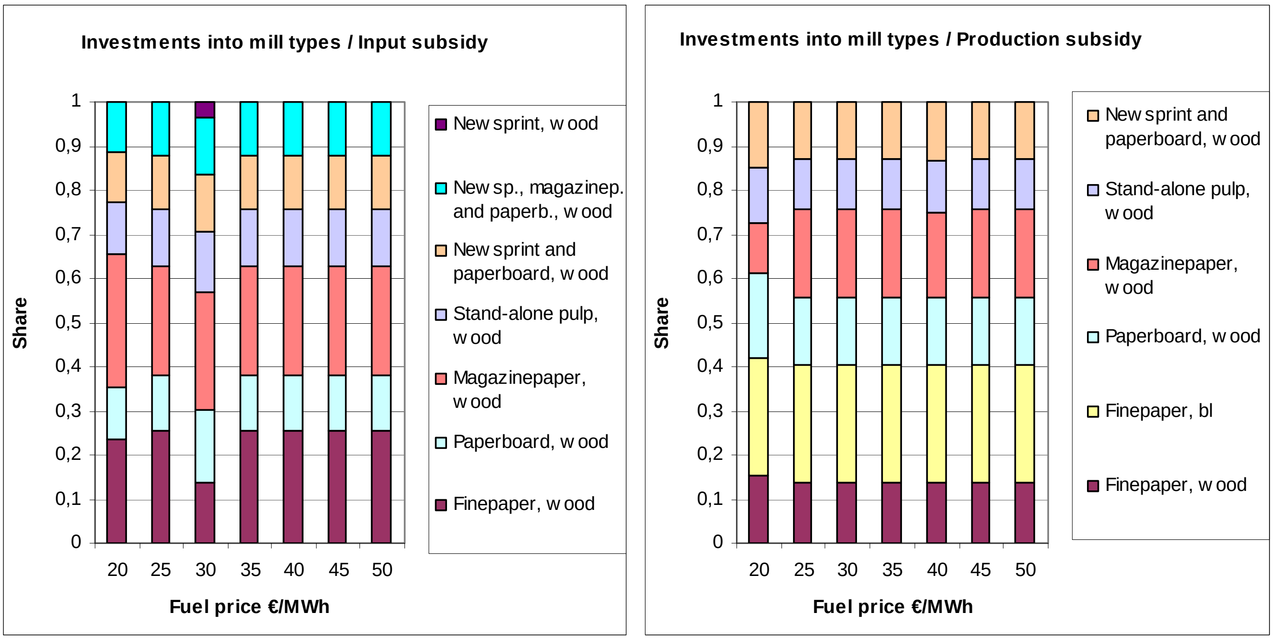

Figure 5. Investments into different mill types. The mill types that are not in the figure, did not invest in biorefinery.

4 Discussion

In this paper, we present a pulp and paper market model that allows investments into biorefineries. The model is used in a numerical application to analyze, what are the effects of different biorefinery promoting subsidies on input use decisions and total policy costs and also, what are the favorable pulp and paper mill types for biofuel production. The numerical application follows the Finnish pulp and paper markets. The results are calculated for fixed annual biofuel production target of 2500 GWh. We analyze three biofuel supporting subsidies: production subsidy, input subsidy for forest residue use and invesment subsidy.

We find that the choice of the policy instrument has many effects. First, the total policy costs of subsidies differ between policies. Second, the biofuel production input choise was affected by the policy choice. Third, the policy choise also had some effect on the distribution of the biorefinery investments among different pulp and paper mill types.

The total supporting costs are lowest in the case of production subsidy and slightly higher for the input subsidy. The total supporting costs of investment subsidy were notably higher than those of the other two subsidies. Although the total supporting costs of production subsidy are lower than those of the forest residual input subsidy, the input subsidy might still be the optimal policy, if there is a policy goal to strongly increase the use of forest residues in energy production. If the goal of the policy is only to support the biofuel production, the production subsidy is the cost-efficient instrument. Therefore, the choice between input subsidy and production subsidy is influenced by the weight that the forest residue use support has in the targets of energy policy. The fuel price impacts the required subsidy levels substantially. Therefore, there should be sufficient knowledge of the future crude oil prices among the policy makers, when the subsidy levels are decided. Other solution is to create the subsidy in a way that its level depends on the fuel price.

In the results, the input choise in biofuel production (wood fiber vs. black liquor) is dominated by the wood fiber. In the case of input subsidy, the biofuel is produced only by forest residual, except for very high fuel prices. In the cases of production and invesment subsidies, also other wood fiber and black liquor were used as inputs. With the production subsidy, the share of wood in the input mix was for most fuel prices about 75 %. These results correspond with the current biorefinery investment plans, since forest biomass is the dominant input in the planned forest biorefineries.

The choice of policy instruments affects the input choice in biofuel production and therefore the investment decisions, since the capital for black liquor and wood fiber based biofuel production are separate. According to our results, those mills having originally existing gas boiler capacity are more favorable for the biofuel production than the others. Some mill types are only favorable in the case of input subsidy, so the policy choise between different subsidies may also impacts which pulp and paper mills invest in biorefinery. In reality, the decision to invest on biofuel production is also affected by local availability of energywood. We do not however include the regional aspect in our analysis.

The transportation sector is not modelled in this study. Therefore, possible increases in carbon taxes in the transportation sector can not be analyzed with this model. Tighter climate policy in the transportation sector would most likely lower the subsidy prices that are required to make forest biorefinery investments profitable.

The choice between different biofuel supporting subsidies has a lot of impacts. We find that investment subsidy is not an efficient policy in compared to input subsidy for forest residue or biofuel production subsidy. However, the weights of different policy goals can influence the choise between production and input subsidy. Therefore, the goals of the biofuel related energy policies should be clear before the decisions of the used policy instruments and their values are made.

Appendix A. The CHP cost functions

There are five possible boiler types in CHP production. The cost function for fluidized bed boiler differs from other boiler types. In the fluidized bed boiler, wood fiber and peat are used as fuels. The wood fiber input costs are separated from the cost function, as in pulp and biofuel production function (see equation 20). The cost function for fluidized bed boiler is

$$c_{fb}(x_{fb}) = p_{peat}x_{peat} + c^{co}\left(\frac{\sum_{w\in WT} z_w}{\sum_{w\in WT} z_w + x_{peat}} - \sigma_{bio}\right)^2 \left(\sum_{w\in WT} z_w + x_{peat}\right) - c^{exo}\left(\sum_{w\in WT} z_w + x_{peat}\right),$$

where *fb* refers to fluidized bed boiler. In a fluidized bed boiler, there are also costs that are related to the joint combustion of the fuels. Those costs are quadratic when deviating from the technically optimal biomass ratio, σ_{bio}. In addition, we include exogenous marginal costs of production, c^{exo} that can be directly connected to the total fuel use, since energy conversion technology is linear. Similar cost structure for co-firing fluidized bed boiler has earlier been used by Kangas et al (2009). For the other boiler types the costs include the fuel input costs (i.e. prices) and exogenous costs.

Appendix B. The Data

Technology parameters for paper and paperboard productions are presented in Table A1. The input uses for production of one unit of output of given paper species are the same, either if it is produced in plant producing one or several paper grades.

Table A1. Technology related parameters for paper and board productions.

	Mechanical pulp input	*Chemical pulp input*	*Recycled pulp input*	*Electricity input*	*Heat input*
Parameter	*a*	*a*	*a*	*a*	*a*
Unit	t/t	t/t	t/t	MWh/t	MWh/t
Fine	0	0,755	0	0,76	1,967
Magazine	0,444	0,255	0	0,741	1,417
Newsprint	0,685	0,062	0,255	0,57	1,417
Paperboard	0,278	0,708	0,029	0,8	1,861

(Carlson, Heikkinen 1998)

The values of parameters describing pulp production technologies are represented in Table A2 for mechanical, chemical and recycled pulp. Mechanical and chemical pulp can be produced with several processes that use one type of wood (pulpwood, chips or dust) in addition of electricity and heat.

Table A2. Technology related parameters for pulp productions.

	Wood input (pulpwood, chips or dust)	*Electricity input*	*Heat input*
Parameter	*1/α*	*a*	*a*
Unit	t/t	MWh/t	MWh/t
Mechanical	1,2	2	-0,53
Chemical	1,8	0,64	3,19
Recycled	1,1 (recycled paper)	0,4	0,1

(Carlson, Heikkinen 1998)

The values of parameters describing technologies in heat and power production are shown in Table A3. Combined heat and power can be produced in fluidized bed boiler, recovery boiler, gas boiler and oil boiler. Also, heat boiler is included.

Table A3. Technology related parameters for heat and power productions.

	Type of plant	*Electricity efficiency*	*Heat efficiency*	*CF cost scale*	*Optimal biomass ratio*	*Exog. costs*
Parameter		η_{el}	η_{heat}	c_{co}	σ	c_{exo}
Unit				€/MWh		
CHP	FB boiler	0,3	0,6	65	0,3	5
CHP	Recovery boiler	0,2	0,4	-	-	0
CHP	Gas boiler	0,4	0,46	-	-	2,5
CHP	Oil boiler	0,3	0,5	-	-	1,5
Heat	Heat boiler	0	0,8	-	-	0

(Finnish Energy Industries 2007, Savolainen, Tuhkanen & Lehtilä 2001, Statistics Finland 2008)

The values of parameters describing biofuel production are represented in Table A4. Biofuel can be produced from wood fibers or black liquor.

Table A4. Technology related parameters for biofuel production.

	Biomass input	*Electricity input*	*Share of by-product gas*
Parameter	*1/α*	*a*	γ_d
Unit	t/MWh	MWh/MWh	
Wood	1.6	0.2	0.24
Black liquor	2.2	0.2	0.24

(Larson et al. 2006, McKeough, Kurkela 2008)

The values of parameters in related to investment costs are represented in Table A5.

Table A5. Investment cost parameters for productions of power and heat, and biofuels.

Type of plant	unit cost of invested capacity	reference level of capacity	elasticity
Parameter	c_{inv}	χ_{calib}	ω_I
Unit	*e/MW/h*	*MW*	
FB boiler for CHP	7,5	80	0,8
Gas boiler for CHP	7,5	100	0,8
Oil boiler for CHP	5,3	60	0,8
Heat boiler	7,5	60	0,8
Biofuel from black liquor	10,0	170	0,8
Biofuel from wood	12,4	207	0,8

(Larson et al. 2006, McKeough, Kurkela 2008, Finnish Energy Industries 2007, Savolainen, Tuhkanen & Lehtilä 2001, Statistics Finland 2008)

Capacities shown in Table A6 determine the maximum level of production for paper and pulp productions. In heat and power production, investments will be added to the original capacity.

Table A6. Capacities of paper, pulp, and heat and power production in all plants.

Type of plant	*News*	*Fine*	*Magaz*	*Board*	*Mech*	*Chem*	*Recycled*	*rec_b*	*fb_b*	*gas_b*	*oil_b*	*heat_b*
Unit	t ton	t ton	t ton	t ton	t ton	t ton	t ton	MW	MW	MW	MW	MW
Fine1	0	1085	0	0	0	370	0	151	280	0	60	163
Fine2	0	850	0	0	0	540	0	220	412	192	0	0
Fine3	0	200	0	0	0	790	0	322	0	120	105	90
Fine4	0	370	0	0	0	210	0	86	78	90	43	0
Fine5	0	200	0	0	0	500	0	204	76	0	96	135
Fine6	0	90	0	0	0	0	0	0	65	0	0	0
Fine7	0	210	0	0	0	0	0	0	0	0	0	60
Fine8	0	80	0	0	0	0	0	0	0	0	0	20
Fine9	0	110	0	0	0	0	0	0	0	0	0	25
Mag1	0	0	580	0	411	720	0	294	129	125	0	106
Mag2	0	0	1260	0	640	150	0	61	160	0	150	0
Mag3	0	0	600	0	300	0	0	0	218	196	0	0
Mag4	0	0	740	0	338	0	0	0	0	211	0	30
News1	80	0	0	0	60	0	157	0	0	0	0	50
Board1	0	0	0	120	0	35	0	14	200	0	185	0
Board2	0	0	0	285	0	0	0	0	120	0	75	0
Board3	0	0	0	205	0	0	0	0	0	68	0	0
Board4	0	0	0	375	0	560	0	229	115	0	115	140
Board5	0	0	0	300	0	290	0	118	90	0	60	60
Board6	0	0	0	100	90	0	0	0	0	0	0	50
FineMag1	0	555	440	0	312	400	0	163	276	0	193	0
FineMag2	460	0	1120	0	850	75	150	30	248	0	158	0
FineBoard1	0	52	0	215	0	0	0	0	113	0	60	0
MagBoard1	0	0	331	920	200	1050	0	429	200	260	0	155
NewsFine1	290	310	0	0	250	225	100	92	300	0	75	80
NewsBoard1	105	0	0	160	100	0	207	0	73	186	0	0
NewsMagBoard1	240	0	185	210	500	0	472	0	218	196	0	0
Pulp1	0	0	0	0	0	655	0	267	254	0	50	20
Pulp2	0	0	0	0	0	650	0	265	0	210	0	0
Pulp3	0	0	0	0	0	300	0	122	0	0	0	88
TOTAL	1175	4112	5256	2890	4051	7520	1086	3069	3625	1854	1424	1272

(RISI 2009, Stora Enso 2009, UPM Kymmene 2009)

The values of parameters for benchmark demands and prices, as well as price elasticities of demand are shown in Table A7. The benchmark data is specified for year 2008.

Table A7. Demand related parameters.

Parameter		*Benchmark demand*	*Benchmark price*	*Elasticity*
Unit		t ton		
Paper	Fine	2 940	639 €/t (world market)	2
Paper	Magazine	5 361	553 €/t	2
Paper	Newsprint	533	441 €/t	2
Paper	Paperboard	2 897	684 €/t	2
Pulp	Chemical	2 378	452 €/t	2
Pulp	Recycled		119 €/t	2
Electricity		300	30 (exog.)	2
Heat		300	25	0,25
Natural gas			21 (exog.)	
Oil			20 (exog.)	
Peat			15 (exog.)	

(Finnish Forest Research Institute 2009)

The values of parameters for benchmark wood supply and prices, as well as price elasticities of supply are shown in Table A8. The benchmark data is specified for year 2008.

Table A8. Parameters for wood supply.

	Benchmark supply	*Benchmark price*	*Elasticity*
Parameter			
Unit	t ton	€/t	
Pulpwood	14 592	81	0,7
Chips	103	61	0,5
Dust	428	43	0,5
Bark	4 512	21	0,5
Residual	1 345	29	0,7
Recycled paper	2 000	119	1

(Finnish Forest Research Institute 2009)

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