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**Renewable energy and climate policies:  
Studies in the forest and energy sector**

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Academic dissertation

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## **ABSTRACT**

This dissertation examines the impacts of energy and climate policies on the energy and forest sectors, focusing on the case of Finland. The thesis consists of an introduction article and four separate studies. The dissertation was motivated by the climate concern and the increasing demand for renewable energy. In particular, the renewable energy consumption and greenhouse gas emission reduction targets of the European Union were driving this work. In Finland, both forest and energy sectors are in key roles in achieving these targets. In fact, the separation between forest and energy sector is diminishing as the energy sector is utilizing increasing amounts of wood in energy production and as the forest sector is becoming more and more important energy producer.

The objective of this dissertation is to find out and measure the impacts of climate and energy policies on the forest and energy sectors. In climate policy, the focus is on emissions trading, and in energy policy the dissertation focuses on the promotion of renewable forest-based energy use. The dissertation relies on empirical numerical models that are based on microeconomic theory. Numerical partial equilibrium mixed complementarity problem models were constructed to study the markets under scrutiny. The separate studies focus on co-firing of wood biomass and fossil fuels, liquid biofuel production in the pulp and paper industry, and the impacts of climate policy on the pulp and paper sector.

The dissertation shows that the policies promoting wood-based energy may have unexpected negative impacts. When feed-in tariff is imposed together with emissions trading, in some plants the production of renewable electricity might decrease as the emissions price increases. The dissertation also shows that in liquid biofuel production, investment subsidy may cause high direct policy costs and other negative impacts when compared to other policy instruments. The results of the dissertation also indicate that from the climate mitigation perspective, perfect competition is the favored wood market competition structure, at least if the emissions trading system is not global.

In conclusion, this dissertation suggests that when promoting the use of wood biomass in energy production, the favored policy instruments are subsidies that promote directly the renewable energy production (i.e. production subsidy, renewables subsidy or feed-in premium). Also, the policy instrument should be designed to be dependent on the emissions price or on the substitute price. In addition, this dissertation shows that when planning policies to promote wood-based renewable energy, the goals of the policy scheme should be clear before decisions are made on the choice of the policy instruments.

**Keywords:** bioenergy, co-firing, emissions trading, energy policy, mixed complementarity problem, partial equilibrium

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Helsinki, November 2011



Hanna-Liisa Kangas

## LIST OF ORIGINAL ARTICLES

This thesis is based on the original papers listed below, which are referred to in the text by their Roman numerals. These papers **I–III** are reprinted with the kind permission of the publishers, while the study **IV** is the author version of the submitted manuscript.

- I** Kangas, H.-L., Lintunen, J. & Uusivuori J. 2009. The Cofiring Problem of a Power Plant under Policy Regulations. *Energy Policy* 37: 1898-1904.  
doi:10.1016/j.enpol.2009.01.028
- II** Lintunen, J. & Kangas, H.L. 2010. The case of co-firing: The market level effects of subsidizing biomass co-combustion. *Energy Economics* 32: 694-701.  
doi:10.1016/j.eneco.2009.11.004
- III** Kangas, H.-L., Lintunen, J., Pohjola, J., Hetemäki, L. & Uusivuori, J. 2011. Investments into forest biorefineries under different price and policy structures. *Energy Economics* 33: 1165-1176. doi:10.1016/j.eneco.2011.04.008
- IV** Kangas, H.-L. 2011. Emission trading under perfect and imperfect input markets: The case of Finnish pulp and paper industry. (Manuscript)

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# 1 BACKGROUND

## 1.1 Introduction

The concern of climate change has led to major changes in energy and climate policies on national, regional and global levels in the last decades. One of the most ambitious climate policy measures has been the initiation of the European Union's emissions trading scheme (EU ETS). In energy policy, the trend of the last decades has been to increasingly promote the use of renewable energy. Climate and renewable energy policies have multiple impacts on industries. For example, the fuel choice of energy production, the input and output prices, the output levels and production structure might be affected by the policies. Also, when considering different policies for promoting renewable energy use, the impacts and costs between different policies can vary. In this dissertation, current issues concerning forest and energy industries and climate and renewable energy policies are examined.

The forest industry is unique when it comes to climate and renewable energy policies. This sector produces both energy and other products, such as pulp and paper. Therefore, the forest industry is closely linked to the energy sector. In fact, the forest industry can use the same input, namely wood, both for energy and industrial production. Thus, climate and energy policies have multiple impacts on the sector, but the impacts of the policies are not always evident.

Both climate policies and policies promoting renewable energy use are aimed at increasing the share of renewable resources in energy production. One of the issues that have been discussed in the context of climate end energy policies is the co-firing of solid fossil fuels and biomass in the existing power plants. Co-firing is seen as a cost-efficient way to increase renewable energy production, since no new investments are needed for the production capacity. Co-firing is thus considered a medium-term solution for decreasing carbon dioxide emissions in countries with substantial biomass resources. However, there is a concern that these policies might also increase the profitability and lengthen the lifetime of existing coal-fired power plants. Thus, the efficiency and carbon intensity of energy production might not improve as a result of promoting co-firing.

Co-firing production is different from other forms of renewable energy production, since the producers can decide on a fuel-mix between fossil and non-fossil renewable fuel, and only the use of the renewable fuel accounts for renewable energy production. Climate policies decrease the profitability of fossil fuel inputs, while policies promoting renewable energy use increase the profitability of renewable inputs. Since there are technical issues concerning the fuel-mix in co-firing power plants, the fuels are not perfect substitutes in the traditional sense. This may have an impact on the relative effectiveness of the policies promoting renewable energy use, when they are aimed at the use of biomass in co-firing. For example, the effects of a feed-in tariff and a feed-in premium on the fuel choice of a co-firing power plant might differ.

The production of liquid biofuels from biomass in second generation biorefineries is one of the key issues of the renewable energy question. Some pulp and paper plants are likely to be transformed into biorefineries, producing liquid biofuels together with their traditional pulp, paper, electricity and heat production. There has been discussion on many alternative policy designs to induce investments into second generation biofuel production, and one can expect that the cost-effectiveness and indirect impacts of these policies vary. There are also concerns related to promoting liquid biofuel production. The reason is that biomass resources

are scarce and thus an increase in liquid biofuel production may reduce biomass use in other energy production.

The impacts of emissions trading on the pulp and paper industry are diverse. First, emissions trading has an impact on the fuel use of the industry: fossil fuels are replaced by wood and this increases the demand for wood in the sector. Second, as a consequence of emissions trading, the wood and energy prices increase and thus the pulp and paper production decreases. This, in turn, lowers the demand for wood in the sector. These impacts may vary according to the input market (i.e. wood market) competition structure of the sector.

## 1.2 Thesis subject matter

In four separate studies, this dissertation examines the impacts of energy and climate policies on the energy and forest sectors. In climate policy, the focus is on emissions trading, and in energy policy the dissertation focuses on the promotion of renewable forest-based energy use. In two studies, the interaction of these policies is also studied. In the numerical models of this study, new renewable energy, needed to fulfil the policy requirements, is produced based on forest-based raw materials or wind. The energy outputs include electricity, heat and liquid biofuels. The objective of this dissertation is to find out and measure the impacts of climate and energy policies on the forest and energy sectors. The impacts on industrial and energy production, wood supply, prices, fuel use and CO<sub>2</sub> emissions are studied. Also, the direct support costs arising from different policies promoting renewable energy are compared in the dissertation.

The study relies on empirical numerical models that are based on microeconomic theory. The models are partial equilibrium market models that give a bottom-up description of the markets under scrutiny. Unlike many other economic models, the technical and physical reality of the production processes is modeled in detail in the studies of this dissertation. The modeling specifications presented in the first study operate as the basis for all the models used in the other studies. Certainly, the models can never give a perfect representation of reality, but they can be used to study the direction, and to some extent the magnitude, of the policy effects and also to compare the costs related to different policy measures.

The separate studies focus on co-firing of wood biomass and fossil fuels, liquid biofuel production in the pulp and paper industry, and the impacts of climate policies on the pulp and paper sector. The topics of the four studies all include both energy and forest sector-related issues.

**Study I** examines how energy and climate policy measures promote an increase in the use of wood biomass in co-firing power plants. Two representative plants are used as examples. The climate policy measure studied is emissions trading and the policies promoting renewable energy use are a feed-in tariff and a feed-in premium for wood use in energy production.

**Study II** compares four renewable energy policy cases based on different combinations of policy strategies and instruments. The strategies differ in respect of the wood biomass co-firing subsidization and the instruments are a feed-in tariff and a renewables subsidy. The results for all four energy policy cases are calculated for different emission permit prices. The partial equilibrium market model includes all the Finnish electricity and combined electricity and heat producers.

**Study III** investigates the possibilities of liquid biofuel production at Finnish pulp and paper plants. Three policy measures inducing the biofuel production unit (biorefinery) investments are compared. The partial equilibrium market model includes all Finnish pulp and paper plants and the related electricity, heat and biofuel production.

**Study IV** examines the effects of emissions trading on the pulp and paper industry under two wood market competition structures: perfect competition and Cournot oligopsony. The impacts on pulp, paper and energy production, as well as on wood markets, are studied. The partial equilibrium market model includes all Finnish pulp and paper plants and the related electricity and heat production.

## 2 OPERATIONAL FRAMEWORK

### 2.1 Energy in Finland

As with other Member States, the framework of Finnish energy and climate policies is decided at the EU level. The European Union has set a binding target for renewable energy consumption: at least 20% of gross final energy consumption must be met by renewable energy by 2020 (EC 2008). Moreover, binding national targets for each EU Member States were given. For Finland, the increase in the use of renewable energy is almost 10 percentage units from the 2005 level (i.e. from 28.5% to 38%). Up to 2010, the increase in the use of renewables has not occurred: indeed the share of renewable sources in final energy consumption was only 26% in 2009 (Finnish Forest Research Institute 2010). Therefore, new policy measures to promote renewable energy are needed to reach the target. Finland has not been one of the pioneers in initiating policy schemes for renewable energy. In fact, Finland (together with Malta) is one of the last EU Member States to introduce a feed-in law or green certificate systems for renewable energy promotion. In addition to the requirement level of renewables of the final energy consumption, the European Union requires that at least 10% of the consumption of liquid transportation fuels should be covered by non-fossil energy by 2020 in each Member State.

The total energy consumption in Finland was 371 TWh in 2009. The most important energy source was oil products, 93 TWh. Wood-based fuels were the second most important energy source (total 74 TWh). The use of wood-based fuels was divided into the use of black liquor and other concentrated liquors in the forest industry (32 TWh), wood use in heat and power plants (26 TWh) and small-scale combustion of wood (16 TWh). The other energy sources include nuclear (68 TWh), coal (43 TWh), natural gas (38 TWh), peat (19 TWh), hydropower (13 TWh), wind power (0.3 TWh) and other (11 TWh). Electricity imports accounted for 12 TWh. Finland's greenhouse gas emissions were 70.1 million tonnes CO<sub>2</sub> equivalent in 2008. The forest industry is a major electricity consumer in Finland. The electricity consumption of this industry in 2009 accounted for 23% of Finnish electricity consumption (19 TWh). The industry itself produced 46% of its electricity consumption and the rest was bought from outside (Finnish Forest Research Institute 2010).

Finland is a part of Nord Pool electricity markets together with Sweden, Norway and Denmark. Nord Pool is considered one of the most competitive power markets globally. In competitive power markets, merit order ranks the production technologies so that the technologies with the lowest marginal costs (i.e. hydro) are the first ones to fulfill the electricity demand. Thus, the electricity supply curve can be characterized as a step function. The electricity market price is determined by the marginal production costs of the marginal technology. The merit order of the production technologies might change due to climate policy. For example, emissions trading can make technologies that use natural gas more profitable than coal-based ones and thus change their merit order (Sijm et al. 2005).

Since Finland is a northern country, the demand for heat is high. Therefore, combined heat and power (CHP) technologies are widely used and well advanced. The share of electricity produced by CHP is about 35% in Finland. The Finnish CHP production technologies yield high energy-efficiency rates (often 90%) (VTT 2007). The co-firing of fossil and renewable fuels is viable especially in fluidized bed combustion boilers (FBC) producing CHP with high energy efficiency. Peat is typically burned in FBC plants in Finland and thus the use of peat could be at least partly replaced by wood-based fuels in the existing plants. The use of co-

firing in Finland is very different from that of, for example, Great Britain, where co-firing is utilized in old coal plants with low energy efficiencies.

Finland has set binding renewable energy targets that require changes in Finnish energy policy. To fulfil these targets, the promotion of renewable energy is needed. The increase in renewable energy production in Finland will be mostly covered by an increase in the use of forest-based raw materials in energy production (Ministry of Employment and the Economy 2010). The use of forest chips is expected to grow notably; the target is to increase the consumption from 6 TWh in 2005 to 25 TWh in 2020. In 2009, the use of forest chips was about 11 TWh.

## 2.2 Wood use and markets in Finland

Forests are a remarkable natural resource in Finland, forestry land accounts for about 86% of Finnish land area. Forests are also a notable income source for a large proportion of Finnish people. Privately owned forests make up about 60% of the forestry land area and there are over 700 000 private forest owners in Finland. The commercial roundwood removals in 2009 were about 41 million m<sup>3</sup>, of which the share of private forests was 77%. The rest of the removals were made in forests owned by forest industries and the state. The major wood user in Finland is the forest industry, i.e. pulp and paper, sawmilling, board and veneer industries. The use of roundwood was about 60 million m<sup>3</sup> in 2009, of which the forest industry used almost 87%. The use of imported wood in the forest industry was around 7 million m<sup>3</sup>. The pulp and paper industry used about 31 million m<sup>3</sup> of roundwood in 2009 (Finnish Forest Research Institute 2010).

In addition to the wood use in the forest industry, wood is also utilized as a fuel in energy production. Indeed, in the last years, wood use has increased mostly in energy production. Heating and power plants used 13.5 million m<sup>3</sup> of wood in 2009. This can be divided into forest chips (5.4 million m<sup>3</sup>), bark (5.4 million m<sup>3</sup>), industrial chips (0.8 million m<sup>3</sup>) and other (0.5 million m<sup>3</sup>) (Finnish Forest Research Institute 2010). The government has set a target of 12.5 million m<sup>3</sup> annual use for forest chips in Finland until 2020. The target is very ambitious when compared to the expected technical and economic potentials (e.g. Pöyry 2007 and 2009, Laitila et al. 2008). Meeting the targets will most likely require collection and harvesting of the raw material of forest chips, i.e. forest residues and small trees and stumps, even from costly forest sites. Additionally, since the supply of forest chips is scarce, and the forest industry is suffering from structural change, the use of pulpwood in energy production might become an issue within this decade.

Since the Finnish pulp and paper industry includes only a few producers and the number of forest owners is substantial, it is possible that the industry will have market power in the wood markets. Indeed, the studies on the wood-market structure of the Finnish and Swedish markets show features of imperfect competition, i.e. oligopsony or monopsony (Bergmann and Brännlund 1995; Kallio 2001). These features appear to be particularly strong, if the economy is in recession. During an economic upswing, the wood markets are found to be more competitive.

## 2.3 Data

The dissertation data was collected from multiple sources and it represents the case of Finland. The Finnish Forest Research Institute provided the data on the wood supply. Statistics Finland and Finnish Energy Industries provided the energy market data, while RISI and the Finnish

Forest Research Institute provided the pulp and paper market data. The models of the two first papers are calibrated for the energy markets in Finland in 2006. The models of the third and fourth paper are calibrated for the energy, wood and pulp and paper markets in Finland in 2008. The data used and the calibrated parameters are provided in detail within each study. We have conducted several sensitivity analyses for each study. The sensitivity analyses have been done for almost all parameters, but with especial interest in the robustness of the results with respect to the calibrated parameters.

The production technology data on energy and pulp and paper production was collected from engineering literature. The main sources for the energy technologies are Flyktman and Helynen (2004), Savolainen (2001) and Larson et al. (2006). The pulp and paper technology data was mainly collected from Gielen and Tam (2006) and Carlson and Heikkinen (1998). The production capacities were taken from the production unit level and the environmental reports of the energy and pulp and paper companies were used here. The price data came from market information on the wood, electricity, heat, pulp, paper, fuel and carbon markets.

The main difference between the models in this thesis and other partial equilibrium energy market models is the cost function specification of co-firing power plants (see also the Appendix). The co-firing power plants are burning peat or coal with biomass (namely, wood). We assume that there is a technically optimal fossil-biomass fuel-mix that minimizes the joint emissions control and corrosion costs. This assumption is based on the fact that biomass prevents the sulphur emissions of fossil fuels and fossil fuel alleviates the corrosion costs caused by biomass. Co-firing is especially optimal when wood and peat are used together (e.g. Hustad et al. 1995, Orjala et al. 2008). The calibrated optimal wood share is 0.0-0.7, depending on the combustion technology and fuels.

In all four studies, wood is the input with the most interest. Transportation costs are a significant part of the costs in the wood supply chain. Thus, the transportation costs are modeled in a quite detailed way. The convex transportation costs are assumed to increase as a square root of wood use. It is assumed that transport costs grow linearly with the distance of the wood delivery and that the wood sources are evenly scattered. Thus, the more that wood is demanded within a plant, the further from the plant the wood is collected from, but the distance grows only in the square root of input use. Therefore, the specification is based on geometry (see also the Appendix). The transportation cost parameter has been calculated from the data provided by Pöyry Energy (2007) and Ranta (2004).

### 3 THEORETICAL FRAMEWORK

#### 3.1 Policy instruments and previous literature

Renewable energy sources have been found to have many advantages over fossil fuels and nuclear power. In contrast with fossil fuel use, renewable energy use contributes to the preservation of public goods, namely, clean air and climate stability. Because these public goods are non-excludable and non-rival, private actors do not have an incentive to invest in them. Therefore, government intervention in the form of policies promoting RES-E<sup>1</sup> is needed to foster renewable energy. Another reason for RES-E policies is that renewable energy is in an unfavourable position in comparison with fossil fuels and nuclear power, because the technology is still, in many ways, immature. RES-E policies are needed to help bring renewable energy to the markets, because once a new technology has been adopted, it becomes more efficient (Menanteu et al 2003). Renewable energy has also been promoted, for example, for reasons of energy supply security and domestic employment. In this dissertation, the motivation for the increase in renewable energy production is exogenous: the renewable energy targets are fixed. We study how to achieve these targets and what are the consequences of different policy strategies and instruments when increasing renewable energy production.

The most common renewable energy promotion schemes in EU Member States are feed-in laws. 21 EU countries have feed-in laws for renewable energy (Fouquet & Johansson 2008). There exists two feed-in laws: feed-in tariff (FIT) and feed-in premium (FIP). Feed-in laws are mostly used to increase the consumption of renewable energy sources in electricity production. Basically, they create an RES-E demand that otherwise would not exist, at least at the same level, and they make RES-E production more profitable. The most common feed-in law is a guaranteed long-term minimum price (€/MWh), i.e. feed-in tariff, for generating electricity with renewable resources. Electric utilities are obligated to purchase RES-E at a tariff price that is determined by the regulators. The idea of FIT is that when electricity producers are assured of a certain long-term minimum price, they are encouraged to invest in immature renewable energy technologies. FITs also provide long-term financial stability to electricity producers and level the volatility and seasonal differences of energy markets. One important feature of FITs is that they can be designed individually for each renewable energy source or technology. That increases the flexibility of FITs, but it can also increase the control costs of a FIT scheme (Lesser & Su 2008; Menanteu et al. 2003).

A feed-in premium is a price that the RES-E producer receives on top of the market price. In this sense, FIP is a more market-based tool than FIT (Muñoz et al. 2007). There are also multiple renewable energy subsidies that give the producers an incentive for renewable energy production equivalent to a feed-in premium. These include a renewables subsidy and production subsidy. In the producers' decisions-making, the above-mentioned policies are all identical to a feed-in premium, but there might be differences in the financing of the policy scheme. In Figure 1, the basic characteristics of FIT and FIP are shown. Both mechanisms increase the price of electricity for RES-E production and thus the supply of RES-E increases.

Lesser and Su (2008) bring out the fact that a feed-in tariff and premium have some similarities. First, both mechanisms guarantee an electricity price that is above the market price. Second, it is inefficient to assure a minimum price forever, so feed-in laws usually have a time limit. Third, the feed-in mechanisms normally have some technological improvement incentives, which make investments profitable. Feed-in tariffs and feed-in premiums are

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<sup>1</sup> RES-E means electricity that is produced by renewable energy sources.

usually paid by electricity utilities. Electricity utilities add the extra price to consumer prices, so the real income transfer is from consumers to RES-E producers.

The major difference between the two feed-in mechanisms is the impact of electricity price change on the RES-E production decision. Figure 2 shows that in the case of FIT, an increase in the electricity price does not give an incentive to increase RES-E production, since the tariff price is fixed. However, in the case of FIP, an increase in electricity price also increases the profitability of RES-E production. Thus, RES-E production also goes up. Since emissions trading leads to an increase in electricity price, this difference between the mechanisms is also important, when considering the interaction between renewable energy and climate policies.

Policies promoting renewable energy have some similarities with climate policy, since they both aim at decreasing greenhouse gas emissions. Therefore, the interaction between these policies is an interesting research question. Theoretical considerations of the interaction between emissions trading and the promotion of renewable energy include, for example, studies by Abrell and Weight (2008), Jensen and Skytte (2003) and Linares et al. (2008). Fischer and Newell (2008) construct a numerical partial equilibrium model to find an optimal policy for climate mitigation. They conclude that due to the knowledge spillovers, the optimal policy includes a portfolio of different policies. In contrast, Böhringer et al. (2009) use the general equilibrium (CGE) model PACE to study the interactions between the EU ETS and the promotion of renewable energy. They find that if the policy target is only to decrease GHG

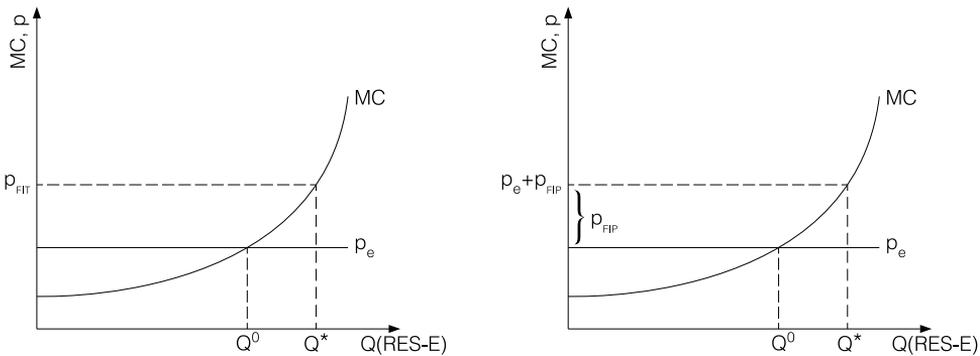


Figure 1. Feed-in tariff (left) and feed-in premium (right).

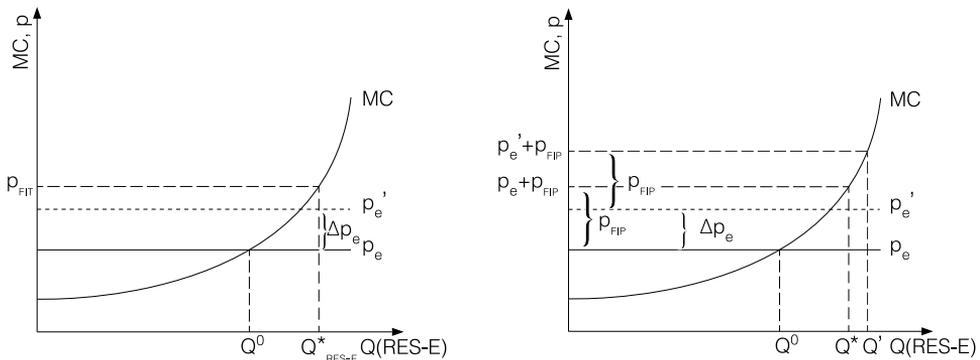


Figure 2. Feed in tariff (left) and feed-in premium (right) and electricity price.

emissions, the use of both climate and energy policy instruments yields higher costs when compared to only using climate policy instrument (EU ETS).

However, in all of the previous studies, the production of energy from renewable and fossil-fuel sources has been separated. Nevertheless, the co-firing of solid fossil fuel and renewable fuel in the same boilers is a very important issue in increasing renewable electricity production (Baxter 2005, Hansson et al. 2009). Lappi et al. (2010) have studied the optimal fuel-mix choice in co-firing power plants under emissions trading, but they did not examine RES-E policies.

### 3.2 Policy analyses for co-firing power plants

#### *Assumptions*

The co-firing power plants are at the core of this dissertation: all four models include co-firing heat and power production with an endogenous fuel-mix choice. The plants can encounter both climate policy and policies promoting renewable energy in their decision-making. The policy instruments analyzed here are the emissions price, feed-in tariff and feed-in premium. The theoretical model presents a co-firing electricity producer using renewable fuel  $z$  and  $\eta$  fossil fuel  $x$ . Some assumptions are made. First, electricity is produced using energy efficiency of the energy conversion process, thus the two inputs are perfect substitutes in production. The output level of the plant is  $y = \eta(x+z)$ . This represents the physical realism of the process. However, there might be slight differences in the energy efficiency depending on the fuel mix, but these are negligible (Baxter 2005, Flyktman and Helynen 2004).

Second, the costs are assumed to be convex  $c(x,z)$ , i.e.  $c_x > 0$ ,  $c_z > 0$ ,  $c_{xx} > 0$ ,  $c_{zz} > 0$ .<sup>2</sup> In the four studies of this dissertation, the costs of the co-firing producer include direct fuel use costs, co-firing costs, and capacity costs. The specification of the costs structure is complex, since it replicates the physical realism of the co-firing process and this implies that the fuels are not perfect substitutes in the traditional sense. The actual cost functions used in the studies fulfil the assumptions of the above-mentioned cost function in all cases except one: if the plant is not utilizing its full capacity. However, this is very unlikely: usually the plants are operating at full capacity or they are not operating at all (see Appendix for proof).

Third, the use of renewable fuel is assumed to be emissions neutral and the use of fossil fuel is assumed to cause carbon dioxide emissions.<sup>3</sup> Therefore, the emissions of the producer are  $e = \varepsilon x$ , where  $\varepsilon$  is the emission factor of fuel  $x$ . The producer has to pay the emissions price  $q$  for each unit of emissions it causes. The emissions price can be interpreted as an emissions permit price or emissions tax. The emissions price impacts electricity price (Sijm et al. 2005). The change in the electricity price can be stated as  $\Delta p_e = qIL$ , where  $p_e$  is the electricity price. The denotation  $I$  is the carbon intensity of a marginal production plant in the electricity markets, i.e. the carbon intensity of the production technology determining the

electricity market price. Thus,  $I = \frac{\bar{\varepsilon}}{\bar{\eta}}$ , where  $\bar{\varepsilon}$  is the emissions factor and  $\bar{\eta}$  the energy

efficiency of the marginal technology. The level of the pass-through of the carbon costs is  $L$ . Therefore, the electricity price that the producer receives is  $p_e = p_e^0 + qIL$ , where  $p_e^0$  is the electricity price, when the emissions price is zero, i.e. pre-policy electricity price.

<sup>2</sup> It is also assumed that  $c_{zz} > c_{xz}$  and  $c_{xx} > c_{xz}$ .

<sup>3</sup> This assumption is in line with EU policy (EU ETS).

*Feed-in tariff*

The co-firing producer receives the electricity price  $p_e$  for each unit of output produced by fossil fuel and the feed-in tariff  $p_{fit}$  for each unit of output produced by renewable fuel. It is assumed that the feed-in tariff is always at least as high as the electricity price, i.e.  $p_{fit} \geq p_e$ . The profits of the producer are thus

$$\pi(z, x) = \left( \frac{x}{x+z} (p_e^0 + qLI) + \frac{z}{x+z} p_{fit} \right) \eta(x+z) - c(x, z) - q\epsilon x . \quad (1)$$

After some manipulation, the first-order conditions can be expressed as:

$$(p_e^0 + qLI)\eta = c_x - q\epsilon \quad (2)$$

$$p_{fit}\eta = c_z \quad (3)$$

Thus, in the optimal input choice, the marginal costs and benefits of the fuels used must be equal.

We next employ comparative statics to examine how the key exogenous variables impact the optimal production choices. The determinant of the Hessian matrix of the maximization problem is  $\Delta = c_{zz}c_{xx} - c_{xz}^2 > 0$ . The comparative statistics of the pre-policy electricity price  $p_e^0$  and fuel used yield

$$\frac{dz}{dp_e^0} = \frac{-\eta c_{xz}}{\Delta} < 0 \quad (4)$$

$$\frac{dx}{dp_e^0} = \frac{\eta c_{zz}}{\Delta} > 0 . \quad (5)$$

An increase in the pre-policy electricity price reduces the use of renewable fuel and boosts the use of fossil fuel. The reduction in the use of renewable fuel originates from the substitution of the fuels, i.e. the interaction of the two fuels in the cost function. Equation (4) shows that even if the feed-in tariff price is fixed, the co-firing RES-E producers are affected by electricity price changes in their decision on renewable fuel use. If the producers were producing only renewable electricity (i.e. wind power), the changes in the electricity price would not have an impact on their production decision under the feed-in tariff (as was seen in Figure 2).

The comparative statistics of the fuels used and feed-in tariff price yield

$$\frac{dz}{dp_{fit}} = \frac{\eta c_{xz}}{\Delta} > 0 \quad (6)$$

$$\frac{dx}{dp_{fit}} = \frac{-\eta c_{zz}}{\Delta} < 0 . \quad (7)$$

As expected, an increase in the feed-in tariff price boosts the use of renewable fuel. At the same time, it reduces the use of fossil fuel. Thus, the feed-in tariff also has an impact on the decision on fossil fuel use.

The comparative statistics of fuels used and emission price yields

$$\frac{dz}{dq} = \frac{-(LI\eta - \varepsilon)c_{xz}}{\Delta} \begin{cases} > 0, \text{ if } \varepsilon > LI\eta \\ < 0, \text{ if } \varepsilon < LI\eta \\ = 0, \text{ if } \varepsilon = LI\eta \end{cases} \quad (8)$$

$$\frac{dx}{dq} = \frac{(LI\eta - \varepsilon)c_{zz}}{\Delta} \begin{cases} < 0, \text{ if } \varepsilon > LI\eta \\ > 0, \text{ if } \varepsilon < LI\eta \\ = 0, \text{ if } \varepsilon = LI\eta \end{cases} \quad (9)$$

The impact of the emissions permit price on the use of the fuels depends on the carbon intensity of the fossil fuel use of the producer, i.e.  $\frac{\varepsilon}{\eta}$  compared to the carbon intensity of the marginal producer times the level of the pass-through of the carbon costs, i.e.  $\frac{\bar{\varepsilon}}{\eta} L$ . If the carbon intensity of the fossil fuel use of the producer is higher than the carbon intensity of the marginal technology times the pass-through level ( $\frac{\varepsilon}{\eta} > \frac{\bar{\varepsilon}}{\eta} L$ ), the increase in the carbon price boosts the use of renewable fuel and reduces the use of fossil fuel. However, if the carbon intensity of the producer is lower than the marginal carbon intensity times the pass-through level, an unexpected effect occurs. In this case, the increase in the emissions price reduces the use of renewable fuel and boosts the use of fossil fuel. The reason is that in the case of the feed-in tariff, the price of the electricity produced by renewable fuel does not increase when the emissions (and electricity) price increases, since the feed-in tariff is fixed. In turn, when the emissions price increases, the price of the electricity produced by fossil fuel also increases. In such a case, the profitability of fossil fuel use grows. Thus, if a co-firing plant is efficient (i.e. has low carbon intensity), it might be profitable to boost the use of fossil fuel even if the emissions permit price increases, if there is a feed-in tariff for biomass use. Therefore, the impact of the emissions price on the electricity price is an important factor, when considering the effects of climate and energy policies.

### *Feed-in premium*

The producer receives the electricity price  $p_e$  for each unit of output produced. In addition, the producer receives the feed-in premium  $p_{fip}$  for each unit of output produced by renewable fuel. Thus, the profits of the producer are

$$\pi(z, x) = \left( p_e^0 + qLI + \frac{z}{x+z} p_{fip} \right) \eta(x+z) - c(x, z) - q\varepsilon x \quad (10)$$

After some manipulation, the first-order conditions can be expressed as:

$$(p_e^0 + qLI)\eta = c_x - q\varepsilon \quad (11)$$

$$(p_e^0 + qLI + p_{fip})\eta = c_z \quad (12)$$

The interpretations of the conditions are similar to the case of the feed-in tariff.

The comparative statistics are analyzed for the same parameters as with the feed-in tariff. The determinant of the Hessian matrix of the maximization problem is also here  $\Delta = c_{zz}c_{xx} - c_{zx}^2 > 0$ . The comparative statistics of the pre-policy electricity price yield

$$\frac{dz}{dp_e^0} = \frac{\eta(c_{xx} - c_{xz})}{\Delta} > 0 \quad (13)$$

$$\frac{dx}{dp_e^0} = \frac{\eta(c_{zz} - c_{xz})}{\Delta} > 0 . \quad (14)$$

An increase in the pre-policy electricity price leads to greater use of both fuels. In the case of the feed-in tariff, the direction of the change was different for the two fuels, but in this case, the direction is the same for both fuels.

In the case of the feed-in premium, the comparative statistics of the premium price yield

$$\frac{dz}{dp_{fip}} = \frac{\eta c_{xx}}{\Delta} > 0 \quad (15)$$

$$\frac{dx}{dp_{fip}} = \frac{-\eta c_{xz}}{\Delta} < 0 . \quad (16)$$

An increase in the feed-in premium price boosts the use of renewable fuel and reduces the use of fossil fuel. Thus, this result is similar to the feed-in tariff.

The comparative statistics of fuels used and the emissions price yield

$$\frac{dz}{dq} = \frac{LI\eta(c_{xx} - c_{xz}) + \varepsilon c_{xz}}{\Delta} > 0 \quad (17)$$

$$\frac{dx}{dq} = \frac{LI\eta(c_{zz} - c_{xz}) - \varepsilon c_{zz}}{\Delta} = ? . \quad (18)$$

An increase in the emissions price leads to greater use of renewable fuel. The effect of the change in the emissions permit price on the use of fossil fuel is not straightforward. On one hand, there is greater use because the increase in the emissions price implies an increase in the electricity price and this makes the production more profitable. On the other hand, the costs of the emissions related to the fossil fuel use lower the profitability of its use. Thus, if the electricity price effect is greater than the carbon cost effect, there is a possibility that the fossil fuel use increases in a co-firing power plant as a consequence of climate policies.

## 4 NUMERICAL MODELING METHODOLOGY

### 4.1 Mixed complementarity problem definition

The methodology of this study is numerical optimization based on microeconomic theory and technical conditions. The models are formulated as mixed complementarity problems (MCP) and the optimization problem is solved using the PATH solver in the General Algebraic Modeling System (GAMS). MCP modeling is a way of generating models for mixtures of equations and inequalities. In a mixed complementarity problem, each function is assigned a complementarity variable. MCP can be used for a variety of engineering and economic problems. For example, the Wardropian or Walrasian equilibrium can be solved. Additionally, nonlinear problems can be modeled with Karush-Kuhn-Tucker (KKT) optimality conditions. The mixed complementarity problem framework allows for policy analyses, where the policy instrument value is endogenous.

The basic mixed complementarity problem definition given here has been modified from those of Billups (1995), Ferris and Munson (2000) and Rutherford (1995). Given a function  $F : R^N \rightarrow R^N$ , and lower and upper bounds  $l, u \in R^N$  ( $-\infty < l \leq u < +\infty$ ), find a complementarity variable  $z \in R^N$  s.t. one and only one of the following holds for each  $j \in \{1, \dots, n\}$ :

$$F_j(z) = 0 \text{ and } l_j \leq z_j \leq u_j \quad (19)$$

$$F_j(z) = 0 \text{ and } z_j = l_j \quad (20)$$

$$F_j(z) = 0 \text{ and } z_j = u_j. \quad (21)$$

The problem can also be written as

$$F_j(z) \perp l_j \leq z_j \leq u_j, \quad (22)$$

where  $\perp$  denotes the complementarity between the function  $F_j(z)$  and the variables  $z_j$  and their bounds.

### 4.2 Producer's problem

A simplified example of a partial equilibrium market and policy model is given here. The problem of the producer  $i \in \{1, \dots, n\}$  is to

$$\begin{aligned} &\text{maximize } \pi_i(y_i) \\ &\text{s.t. } y_i \leq y_i^{\max}, y_i \geq 0, \end{aligned} \quad (23)$$

where  $y_i$  is the output and  $y_i^{\max}$  is the production capacity of producer  $i$ . Thus, the bounds of the variable  $y_i$  are  $0 \leq y_i \leq y_i^{\max}$ . The profit function  $\pi_i(y_i)$  is twice continuously differentiable. Thus, one and only one of these must hold

$$-\frac{\partial \pi_i(y_i)}{\partial y_i} = 0 \text{ and } 0 \leq y_i \leq y_i^{\max} \quad (24)$$

$$-\frac{\partial \pi_i(y_i)}{\partial y_i} \geq 0 \text{ and } y_i = 0 \quad (25)$$

$$-\frac{\partial \pi_i(y_i)}{\partial y_i} \leq 0 \text{ and } y_i = y_i^{\max} . \quad (26)$$

The equation (24) represents the interior solution of the maximization problem, where the derivate is stationary. The equations (25) and (26) represent the boundary solutions. If the profit maximizing point of the production  $y_i$  is at its lower bound (in this case zero), the profit function  $\pi_i(y_i)$  must be decreasing as production  $y_i$  increases. Therefore, the derivate of the negative of the profit function must be at least zero (equation 25). The opposite holds for the upper bound (equation 26).

The model can also be formulated through the Lagrangian function and KKT conditions. The Lagrangian of the problem is<sup>4</sup>

$$L_i(y_i, \lambda_i) = \pi_i(y_i) - \lambda_i(y_i - y_i^{\max}) , \quad (27)$$

where  $\lambda_i$  indicates the Lagrangian multiplier (and the complementarity variable) of the capacity constraint. The complementarity variable of the profit function is the output amount. The KKT conditions are thus

$$\begin{aligned} \frac{\partial L_i}{\partial y_i} = \frac{\partial \pi_i(y_i)}{\partial y_i} - \lambda_i \leq 0 \quad y_i \geq 0 \quad \text{and} \quad y_i \frac{\partial L_i}{\partial y_i} = 0 \\ \frac{\partial L_i}{\partial \lambda_i} = y_i^{\max} - y_i \geq 0 \quad \lambda_i \geq 0 \quad \text{and} \quad \lambda_i \frac{\partial L_i}{\partial \lambda_i} = 0 \end{aligned} \quad (28)$$

These KKT conditions are equal to the problem description presented in the equations (24)–(26). If the producer produces good  $y$ , i.e. the production is positive, the corresponding first order condition equals zero. The Lagrangian multiplier of the capacity constraint  $\lambda_i$  has a positive value, if the globally optimal production level of the profit maximization problem is greater than the production capacity  $y_i^{\max}$ . In other words, if the producer would profit from producing more than its capacity, the capacity constraint is binding and its shadow price is positive. In this case, the production equals the capacity and thus the capacity constraint condition equals zero.

Since the models dealt with in this dissertation also include new technologies, investment options for new capacity are important. The way that the investments are included in the MCP model in this dissertation is presented here. The investments increase the existing capacity. It is important to note (especially in the case of new technologies) that the existing capacity can be zero. The profit maximization problem is now to

$$\begin{aligned} \text{maximize } \pi_i(y_i, I_i) \\ \text{s.t. } y_i \leq y_i^{\max} + I_i, y_i \geq 0, I_i \geq 0, \end{aligned} \quad (29)$$

where  $I_i$  indicates investments into new capacity. Now the Lagrangian function is

$$L_i(y_i, \lambda_i, I_i) = \pi_i(y_i, I_i) - \lambda_i(y_i - y_i^{\max} - I_i) . \quad (30)$$

The KKT conditions of the problem yield

<sup>4</sup> The KKT conditions are discussed, for example, in Chiang (1984).

$$\begin{aligned}
\frac{\partial L_i}{\partial y_i} = \frac{\partial \pi_i(y_i, I_i)}{\partial y_i} - \lambda_i &\leq 0 & y_i &\geq 0 & \text{and} & y_i \frac{\partial L_i}{\partial y_i} &= 0 \\
\frac{\partial L_i}{\partial I_i} = \frac{\partial \pi_i(y_i, I_i)}{\partial I_i} + \lambda_i &\leq 0 & I_i &\geq 0 & \text{and} & I_i \frac{\partial L_i}{\partial I_i} &= 0 \\
\frac{\partial L_i}{\partial \lambda_i} = y_i^{\max} + I_i - y_i &\geq 0 & \lambda_i &\geq 0 & \text{and} & \lambda_i \frac{\partial L_i}{\partial \lambda_i} &= 0
\end{aligned} \tag{31}$$

If the production level is below the initial capacity at the global maximum of the profit maximization problem, the investments  $I_i$  and also the shadow price of the capacity constraint  $\lambda_i$  are zero. Thus, the production is lower than the initial capacity and the first order condition of the investment decision is negative. If the global maximum yielding production is greater than the initial capacity, the Lagrangian multiplier  $\lambda_i$  is positive and the production equals the capacity. In this case, the investments can be zero or have a positive value, depending on the investment costs and the value of the Lagrangian multiplier  $\lambda_i$ . This is because in the first order conditions of the investment decision, the derivate of the profit function with respect to investments can be interpreted as the first derivate of the investment costs  $\frac{\partial \pi_i(y_i, I_i)}{\partial I_i} \leq 0$  and the Lagrangian multiplier is  $\lambda_i \geq 0$ . Thus, investments are positive, if  $\frac{\partial \pi_i(y_i, I_i)}{\partial I_i} = \lambda_i$ .

Therefore, the tighter the capacity constraint is and the lower the investment costs are, the more likely the producer will invest in new technology.

### 4.3 Market clearing and policy restrictions

The market is cleared through equilibrium conditions. Usually, the demand for the final goods is given as exogenous demand relation in partial equilibrium models and this approach is also used here. Therefore, in market equilibrium, for each output, the sum of the productions of all the producers must equal or be greater than the demand. In this example, there exists only one output, but it is easy to include other outputs in the model. The profit maximization of the producers can also be formulated in a way that the producer chooses the input use of the production instead of the output amount. Then, a production function describes the input-output relation of the production process. In this case, there exists also a demand for inputs. The supply for inputs can be handled with a fixed price or supply relation (i.e. supply function). In the studies of this dissertation, the main input with a supply relation is wood. However, in the example model, the producers make only output decisions. Nevertheless, the input demand and market equilibrium are modeled in the same manner as the output case discussed here.

The supply  $S$  of the product  $y$  is the sum of the productions of all the producers

$$S = \sum_{i=1}^n y_i . \tag{32}$$

The demand  $D$  is given as exogenous demand relation, i.e. demand function

$$D = d(p), \tag{33}$$

where  $p$  is the price of output  $y$ . The market equilibrium is thus given as

$$S \geq D \perp p, \quad (34)$$

where price is the complementarity variable of the market clearing condition.

The mixed complementarity problem type allows for endogenous policy instrument values. The policy instrument levels can be endogenous in the model, if there is a known policy target for the output (e.g. biofuels). Thus, a condition may exist where this target has to be obtained. The shadow price of reaching this target (the complementarity variable of the condition) can be interpreted as the policy instrument value. In this dissertation, the subsidies promoting renewable energy are, in most cases, endogenous in the models. Next, a specific feed-in premium example is given. Imagine that the government wants to guarantee a minimum production level of  $\hat{y}$  for the production of output  $y$ . This gives a new restriction to the model, i.e.

$$S = \sum_{i=1}^n y_i \geq \hat{y} \perp p_{fip} \geq 0, \quad (35)$$

where the Lagrangian multiplier, i.e. the shadow price of the policy restriction can be interpreted as the feed-in premium level. If the production of  $y$  reached the target level without the policy target restriction, the premium level is zero. If the policy instrument is needed to reach the target level of production, the premium level is positive and the producers receive the premium price for each unit of production of good  $y$ . Thus, in the producer problem, the profit function is now

$$\pi_i(y_i, I_i) = \Pi_i(y_i, I_i) + p_{fip} y_i, \quad (36)$$

where  $\Pi_i(y_i, I_i)$  indicates the semi-profit function without the policy benefits of the producer  $i$ . If the costs of the support scheme are allocated to all users, the unit support costs should be included in the demand function.

## 5 SUMMARIES OF THE STUDIES

### Study I. The cofiring problem of a power plant under policy regulations

The co-firing of biomass and solid fossil fuels is one of the most promising ways to increase renewable electricity (RES-E) production in the short run. In this study, the most popular policy mechanisms promoting RES-E – the feed-in tariff and feed-in premium – are studied together with emissions trading in the co-firing context.

There are two main technologies for co-firing: pulverized fuel (PF) and fluidized bed combustion (FBC). Both technologies support co-firing, but in the PF boilers only a small share of the fuel-mix can consist of biomass. In the study, both technologies are examined through representative power plants. In the PF boiler, coal is co-fired with wood and in the FBC boiler, peat is co-fired with wood. A numerical MCP model is used to represent the fuel choice of the representative power plants under policy regulations.

If wood use in co-firing replaces fossil fuel use, the share of renewable energy in the energy-mix increases and the CO<sub>2</sub> emissions related to energy production decrease. A policy promoting RES-E for wood use in co-firing is needed, since the price of wood is usually higher than that of coal or peat. Additionally, the transportation costs of wood are notably higher than those of its substitutes. Increasing the wood share in the fuel-mix might also increase the maintenance costs of co-firing power plants, especially in the case of PF technology.

The climate policy instrument examined in this study is emissions trading. The results are calculated for emissions prices ranging from 0-100 €/tCO<sub>2</sub>. Since the emissions prices and electricity markets are exogenous in the study, the impact of the emissions permit price increase on the electricity price is taken into consideration with the pass-through rate.

The RES-E policy instruments studied are feed-in laws, namely the feed-in tariff (FIT) and feed-in premium (FIP). The feed-in tariff is a fixed price which the producer receives for RES-E production instead of the electricity price. The feed-in premium is a fixed premium price on top of the electricity price for RES-E production. The FIT and FIP prices are exogenous in the study and they are fixed for the same level for all the emissions and electricity prices.

The study shows both in a theoretical and numerical framework that in the case of FIT, it is possible for the producers to be in a situation where increasing the emissions price reduces biomass use in co-firing. This situation requires a high pass-through rate and efficient technology from the power plant in question. The reason behind the reduction in the use of biomass is the increasing profitability of fossil fuel use, when the emissions price (and electricity price) increases. The same profitability increase for biomass use is not possible with FIT, since the RES-E price (i.e. FIT) is fixed and does not rise along with the emissions (and electricity) price. In the case of FIP, it is not possible to have a reduction in biomass use, since an increase in the emissions price also increases the price that the producer receives for RES-E.

The results show that the interaction between FIT and emissions trading may lead to an unwanted situation where biomass use drops when the emissions price increases in certain power plants. There is also a risk with FIP: if the emissions price is high, there is a risk of overcompensating biomass use in co-firing. This problem can be avoided if the FIP price depends on the emissions price, so that the FIP price would decrease when the emissions price increases.

## **Study II. The case of co-firing: The market level effects of subsidizing biomass co-combustion**

Co-firing can increase the use of renewable biofuels cost-efficiently, but there are also concerns related to it. The concern is that promoting biomass use in co-firing power plants increases the profitability of existing coal- and peat-using plants and thus prevents new investments in renewable electricity (RES-E) production. This might also lead to an energy production structure where the carbon-intensity of the production would not decrease as a consequence of RES-E promotion. Given these concerns, co-firing is not a part of the RES-E policy schemes in all countries.

In this study, the model of the first study of the thesis is extended to the electricity market level, to find out the market level impacts of the promotion of co-firing. The endogenous energy production technologies of the model include pulverized fuel and fluidized bed combustion, i.e. co-firing technologies using coal, peat and wood. In addition, natural gas and wind power production are endogenous in the model. For the endogenous technologies, investments in new capacity are allowed. Nuclear power and hydropower production are exogenous in the model.

The RES-E instruments studied are the feed-in tariff and a renewables subsidy (or feed-in premium). The results are calculated for four separate policy cases: (1) co-firing is not subsidized and the RES-E policy is FIT; (2) co-firing is not subsidized and the RES-E policy is a renewables subsidy; (3) Co-firing is subsidized and the RES-E policy is FIT; (4) co-firing is subsidized and the RES-E policy is a renewables subsidy. When co-firing is not subsidized, the RES-E policy is targeted only to wind power and when co-firing is subsidized, both wood use in co-firing and wind power are subsidized. In all four policy cases, there is a production target of 30% for RES-E of the total electricity production. The level of the RES-E policy instrument is determined endogenously in the model. In all the four policy cases, emissions trading is present and the results are calculated for emissions prices of 0-60 €/tCO<sub>2</sub>.

The results show that the decision on whether to include or exclude the wood use in co-firing in the RES-E policy scheme, does not impact the carbon intensity of energy production significantly. However, if wood use in co-firing was included in the RES-E scheme, the investments in wind power were lower than if co-firing was excluded from the RES-E scheme. This result was particularly strong for low emissions prices.

The direct policy costs of the RES-E scheme were lower if wood use in co-firing was subsidized than if it was not. The costs were slightly lower under a renewables subsidy than FIT, if co-firing was included in the RES-E scheme. If co-firing was excluded from the RES-E scheme, the costs of FIT and the renewables subsidy were identical. With FIT and co-firing in the RES-E policy scheme, the results show that increasing the emissions price does not cause the required FIT price level to decrease. The reason is that with FIT, the pass-through effect does not increase the profitability of wood use.

The policy schemes also impact the fuel use in the energy markets. An increase in the emissions price leads to a reduction in peat and coal use and an increase in natural gas use in all four studies. For wood use, the results are different depending on the inclusion of co-firing in the RES-E scheme. If wood use in co-firing is excluded from the RES-E scheme, an increase in the emissions price boosts wood use, since emissions trading is the only means of increasing the profitability of wood use. If co-firing is included in the RES-E scheme, an increase in the emissions price reduces wood use in energy production. This has resulted from the decreasing utilization rate of coal- and peat-fired co-firing power plants as the emissions price increases.

The results show that if biomass use is included in the RES-E scheme, this does not automatically increase the profitability of coal and peat power plants, if the RES-E scheme is introduced together with the emissions trading scheme. However, the inclusion of co-firing into the RES-E scheme does decrease the investments in wind power. The main result of the first study, namely, the fact that FIT prevents the co-firing RES-E producers from receiving the profitability impacts caused by the pass-through effect, was also seen in this study.

### **Study III. Investments into forest biorefineries under different price and policy structures**

The third study examines the liquid biofuel production possibilities in the pulp and paper industry. Policy targets have been set to initiate production, but the uncertainty of the policy measures for promoting use places restraints on investments in the capacity. In the study, three different policy instruments for promoting biofuel use are examined: production subsidy, input subsidy and investment subsidy. The production subsidy is received for each unit of liquid biofuel that is produced. The input subsidy is given for each unit of forest residues used in the liquid biofuel production process and the investment subsidy is a share of investment costs paid by the government. The direct support costs and other impacts of the policies are specified and compared in the study.

The methodology used in the study is the numerical MCP partial equilibrium pulp and paper market model. The producers in the model are able to produce pulp, paper, electricity, heat and liquid biofuels. The initial capacity to produce liquid biofuels is zero for all producers, but capacity investments are possible for liquid biofuel and electricity and heat production capacity. The electricity and heat production processes of the study follow the approach of the first two studies of the thesis. The data follows the Finnish pulp and paper industry in 2008.

The results show that the biofuel production capacity investments are close to being profitable in Finland, but support is needed to induce the investments. Of the three policy instruments studied, the production subsidy would have the lowest support costs. The direct support costs of the input subsidy were higher than those of the production subsidy. However, the input subsidy increased the use of forest residues efficiently. According to the results of the study, the investment subsidy was problematic, since the producers were not willing to invest in technologies for producing liquid biofuels in some cases, even with an investment subsidy of 100%. This was due to the high production costs of liquid biofuel production compared to the investment costs.

The use of wood fiber types varied for the different policy instruments: for example, under the input subsidy, the use of wood for liquid biofuel production consisted only of forest residues. Under the production and investment subsidies, the use of wood fiber was more diverse and even small amounts of pulpwood were used in the production. The biofuel production caused the CO<sub>2</sub> emissions of the sector to increase, since the plants shifted partly from wood use in electricity and heat production to fossil fuel use. Therefore, the promotion of liquid biofuel production does not necessarily decrease the total CO<sub>2</sub> emissions.

#### **Study IV. Emissions trading under perfect and imperfect input markets: The case of the Finnish pulp and paper industry**

Emissions trading has impacts on the industries included in the scheme, but the impacts might differ according to the competition structure of the input market. The Finnish pulp and paper industry is an example of an industry where the competition structure shows features of oligopsony and the industry is also a part of the EU emissions trading scheme. Therefore, it makes a representative case when studying the impacts of emissions trading on an industry under different input market structures.

In the fourth study, the impacts of emissions trading on the Finnish pulp and paper industry are studied under both perfect competition and oligopsony in pulpwood and industrial chips markets. The methodology of the study is numerical MCP modeling. The models used in this study are based on the model used in the third study. However, there are no investments in liquid biofuel production, since the policies promoting biofuel use are not included in this study. The data follows the year 2008 and all Finnish pulp and paper producers are included in the study. The results are calculated for emissions prices of 0-100 €/tCO<sub>2</sub>.

The results show that emissions trading decreases the pulp and paper production under both competition structures, but the relative decrease is greater under oligopsony than under perfect competition. Emissions trading has a two-fold impact on the wood use of the sector. On one hand, emissions trading increases wood use in energy production, since wood replaces fossil fuels. On the other hand, the decrease in pulp and paper production lowers the demand for wood. Under perfect competition, the decrease in wood use in pulp production was smaller and the increase in wood use in energy production was higher than under oligopsony. Thus, the industry was able to adapt to the changing conditions better under perfect competition than under oligopsony. The higher the emissions permit price was, the stronger were the results. This implies that if there is oligopsony power in the sector, it would be less vulnerable to carbon leakage. Thus, it seems that perfect competition is the favored competition structure, if the emissions trading scheme is not global, not only for the economic welfare, but also for mitigating impacts from climate change.

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## APPENDIX: COST FUNCTION SPECIFICATIONS

In the models of this dissertation, the costs of the co-firing producer include direct fuel use costs, co-firing costs, and capacity costs. The cost function specification is complex and it is presented here piece by piece. In this chapter, the assumptions of the cost function of the theoretical framework are tested for the main model specifications.

Direct fuel input costs include the fuel prices and the wood transportation costs

$$C^{dir} = c_z^{dir} + c_x^{dir} = v z + \frac{2}{3} t_z z^{\frac{3}{2}} + w x, \quad (A1)$$

where  $v$  and  $w$  are the prices for renewable fuel (i.e. wood) and fossil fuel, respectively. The wood transportation cost parameter is  $t_z$ . Wood is a spread-out resource and thus its use generates significant transportation costs. The convex transportation cost specification assumes evenly distributed wood resources. It is also assumed that the transportation costs increase linearly with the distance of wood delivery. Therefore, the number of wood sources in a circle of given radius grows to the square of the radius. Thus, the value  $\frac{3}{2}$  is based on geometry.

For the co-firing power plants, there are costs that are related to the physical burning of the fuels. For this reason, a co-firing cost term is included. The maintenance and abatement costs of a co-firing power plant are assumed to increase as the total fuel use increases. We also assume that there is a technically optimal ratio of the fuel-mix that minimizes the joint emissions control and corrosion maintenance costs. If the fuels are used in the technically optimal ratio, the co-firing costs are zero. This is important especially when co-firing peat and wood. Wood fuel prevents sulphur emissions of peat, but peat decreases the corrosion costs related to the burning of wood (Hustad et al. 1995, Ojala et al. 2008). Therefore, in the cost specification, the fuels are not perfect substitutes. The quadratic co-firing cost specification is

$$C^{co}(x, z) = c^{co} \left( \frac{z}{x+z} - \sigma_z \right)^2 (x+z), \quad (A2)$$

where  $\sigma_z$  is the optimal ratio (i.e. the ratio yielding the minimum unit costs) of renewable fuel (i.e. wood) in the fuel-mix.

There are also capacity costs related to the producer's problem. The capacity costs are taken into consideration in two different ways in the dissertation. This analysis follows the approach of the first study, where the capacity costs are given by a function

$$C^{cap}(x+z; K) = \kappa \left[ (1-\chi) \frac{1-(1-\chi)^{-a}}{a} + \chi \right] K, \quad (A3)$$

where  $K$  is the capacity,  $\chi = \frac{x+z}{K}$ , is the utilization rate of the plant and  $a \in (0,1)$  and  $\kappa$  defines the shape of the function. The function is similar to that of Golombek et al. (1995), except that the parameter  $a$  gives more flexibility to the exact shape of the costs. In fact, the formulation of Golombek et al. is a limiting case of our cost term when  $a \rightarrow 0$ .

With these assumptions, the first derivatives of the cost function are

$$c_x = w + c^{co} \left( \frac{z}{x+z} - \sigma_z \right) \left( -\frac{z}{x+z} - \sigma_z \right) + (a-1) K \frac{1-(1-\chi)^{-a}}{a} \quad (A4)$$

$$c_z = v + t_z z^{\frac{1}{2}} + c^{co} \left( \frac{z}{x+z} - \sigma_z \right) \left( 2 - \frac{z}{x+z} - \sigma_z \right) + (a-1)K \frac{1-(1-\chi)^{-a}}{a} \quad (\text{A5})$$

The first derivatives of the cost function might be positive or negative. The first derivative of the fossil fuel  $x$  may be negative, if  $\frac{z}{x+z} > \sigma_z$ , i.e. if in the fuel-mix, the share of renewable fuel is greater and the share of fossil fuel is smaller than their optimal shares. In this case, the marginal costs of fossil fuel use might decrease, if fossil fuel use increases. However, even with a negative marginal co-firing cost term, the relative importance of marginal direct fuel use costs and capacity costs may be greater, and in this case the first order conditions are positive. The same holds for the renewable input  $z$ , except that the marginal costs may be negative, if  $\sigma_z > \frac{z}{x+z}$ .

The second derivatives of the cost function are

$$c_{xx} = \frac{2c^{co}x^2}{(x+z)^3} + \frac{(1-a)\kappa(1-\chi)^{-a}}{K-x-z} \quad (\text{A6})$$

$$c_{zz} = \frac{1}{2}t_z z^{-\frac{1}{2}} + \frac{2c^{co}x^2}{(x+z)^3} + \frac{(1-a)\kappa(1-\chi)^{-a}}{K-x-z} \quad (\text{A7})$$

$$c_{xz} = c_{zx} = -\frac{2c^{co}xz}{(x+z)^3} + \frac{(1-a)\kappa(1-\chi)^{-a}}{K-x-z} \quad (\text{A8})$$

The second derivatives (A6) and (A7) are always positive, and this follows the assumptions given in Section 3.2. The second derivative (A8) may have a negative value, if the negative impact from the co-firing cost term is greater than the positive impact from the capacity cost term. Therefore, the results of the equations (16) and (17) in Section 3.2 may not hold in the previously mentioned case. However, this situation is very unlikely, and it can only occur, if the plant is not utilizing its full capacity, since  $\lim_{(K-x-z) \rightarrow 0} \frac{(1-a)\kappa(1-\chi)^{-a}}{K-x-z} = \infty$ .

In the comparative statistics part, the results for the equations (13), (14) and (17) required the assumptions  $c_{xx} > c_{xz}$  or  $c_{zz} > c_{zx}$  and this is true for all cases, since

$$c_{xx} - c_{xz} = \frac{2c^{co}x^2}{(x+z)^3} + \frac{2c^{co}xz}{(x+z)^3} > 0 \quad (\text{A9})$$

$$c_{zz} - c_{zx} = \frac{1}{2}t_z z^{-\frac{1}{2}} + \frac{2c^{co}x^2}{(x+z)^3} + \frac{2c^{co}xz}{(x+z)^3} > 0. \quad (\text{A10})$$

The comparison of the cost structure and the theoretical model show that the results of Section 2.2 hold in almost all situations in the models, the only exception being one where the plant is not utilizing its full capacity.