Exploring Energy Flexibility in the Norwegian Pulp and Paper Industry

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ABSTRACT

A bottom-up energy systems model is built up for the Norwegian pulp and paper Industry. Each mill is modelled separately, and energy use is split up by product and end use. Investments in boilers, backpressure turbines and use of energy carriers (electricity, oil, and biomass) are calculated endogenously based on a discounted least cost procedure for the total system costs. The pulp and paper sector has high energy flexibility, because process steam can be produced in boilers, and from many energy sources. Imposing taxes on electricity and oil use, biomass use increases significantly. Investment subsidies for boilers have to be large to obtain the same effect.

Background

Norwegian electricity supply is dominated by hydropower. More than 99% of the production is generated from water turbines installed up in the mountains or along rivers. The reservoirs generally secure supply even during the winter, when there is little or no inflow to the dams and the consumption is largest. There even exist so-called multi-year dams, but these can only to a certain extent relieve the situation caused by a very dry year.

Therefore energy flexibility, or the ability to switch between different energy carriers, is essential to the Norwegian energy system. Especially the pulp and paper sector is known to rapidly adjust the electricity-fuel mix according to relative prices between relevant energy carriers. Studying energy use and capital stock (installation of boilers and turbines) in this sector, is important for revealing possibilities for controlling electricity use during extreme climatic situations.

Although Norway is a country with extraordinary energy resources, domestic electricity supply has not managed to keep up with the growing consumption in the last decade. In a mean year (i.e. when it comes to temperature and precipitation) there is now (2000) a shortage of more than 6%. Imported electricity, which can be regarded as marginal production, is most probably produced from coal in Denmark. The objective of reducing global CO_2 emissions therefore calls for a national effort to switch to more domestic renewables, in particular use of biomass. Also in this respect the pulp and paper industry is expected to have a large potential for a more extensive utilization of this energy resource, and at a relatively low cost.

In the pulp and paper industry biomass is primarily used as a raw material, but byproducts as barking waste, wood waste and black liquor is also used as boiler fuels for generating process heat or even electricity. Some biomass therefore exists on site for free, or even with a negative alternative cost (costs for deposition etc.). Also processed industrial or municipal wastes, as well as bark and wood chips from sawmills can be utilized as fuel for the large boilers. In the future, even wood cut by the sole reason of energy supply, might be economical if appropriate energy policies are implemented. Such a measure can be a uniform per ton CO_2 tax on fossil fuels.

The short and long term energy flexibility of the pulp and paper industry is important for regulating peak power demand, the annual adaption to the percentage of filling of the hydro reservoirs, as well as the long term transition to a more sustainable energy use.

There exist many studies on energy efficiency in the pulp and paper industry (e.g. Farla et.al. 1997 and de Beer et.al. 1998), but models for analyzing the energy flexibility in this sector are more rare.

An exception is a description of a static resource flow model of the Finnish pulp and paper industry (Tamminen & Forsström 1988). Here, not only energy resources are accounted, but also chemicals, by-products and the mass flow from raw wood to products. The reason for this complicated structure is that wood can be used as raw material both for energy and products. Also, manufacturing of chemicals is energy consuming, and chemicals can also be re-cycled when black liquor is recovered as energy. Finally the flow of by-products forms a reverse stream of energy in the system.

Parts of this structure are included in the national Finnish EFOM Model (Lehtilä and Pirilä 1996). Here, the description of the pulp and paper sector includes 13 different pulp qualities and 10 different categories of paper and board products.

An Energy end-use model for pulp, paper and paperboard mills is presented by Giraldo & Hyman, 1995 and 1996. The model is based on process-step energy-consumption, with data from the U.S. Department of Energy's 1991 Manufacturing Energy Consumption Survey (MECS). Material flows and energy consumption of different process-steps are central in this model.

Another model is presented by Ruth et.al. 2000. Their model is used to assess possible impacts of climate-change policies on energy use and carbon emissions in the US pulp and paper industry.

Model Description

The main objective of our pulp and paper model is to examine energy flexibility and its connection to the capital stock. Flexibility is generally restricted to thermal energy use and in particular production of steam. Steam is produced in boilers and can be generated by almost any source or energy carrier: Electricity, oil, biomass (bark, black liquor and other bio-wastes) and recovered vapour from TMP production. There is full flexibility in switching from one fuel to the other, as long as the appropriate boiler types and energy resources are present. Since flexibility is being bounded by the installed equipment, we have tried to model the installation and retirement of boilers.

The model also contains a detailed description of autoproduction of electricity. Autoproduction occurs mainly in mills producing chemical pulp, and which have surplus of black liquor.

Biomass can be internal or purchased from outside. Of the internal biomass black liquor is the most important. Internal energy in each mill (bark, black liquor, TMP-vapour, sludge etc) is restricted by the production through a fixed ratio for each mill. External biomass can be purchased at prices which cover costs for harvesting and transport.

Electricity, oil and coal use is bought at fixed, exogenously given prices. A few mills buy steam. Some mills also sell steam or electricity outside the pulp and paper sector.

In order to capture the distribution of the installation year of the capital stock and the inhomogeneity in the sector, 12 large mills are modelled individually. 7 small paper mills are merged into one group and two small ground wood mills constitute the last unit.

For each mill energy use is split up by product (chemical pulp, ground wood pulp, C/TMP, paper and board) and energy services (steam, electricity and direct use of oil), giving a total of 15 end use blocks, see appendix 1. Net demand (for instance useful steam delivered from the boilers) in the base year is calculated from actual (purchased and internal) energy use multiplied by mean conversion efficiency of energy equipment in place. The base year is 1996, representing the period from 1994 to 1997.

There are totally nine periods. The last ends in 2030. Net demand of energy service for each block is given exogenously. Except for the base year, use of energy and investments in energy equipment are decided endogenously. When there is need for re-investments, a new boiler is selected.

The MARKAL Model

The model is constructed within MARKAL (Fishbone and Abilock 1981), which is a framework for describing energy systems as energy flows between technologies or processes (Marcuse et al. 1976). MARKAL is developed within the framework of the Energy Technology System Analysis Program (ETSAP) of the International Energy Agency, and has been used actively in more than thirty countries.

The model describes a linear system of equations balancing supply and demand for any primary or secondary energy carrier, as well as user-defined constraints for technologies and emissions from the energy system. The model is optimized minimizing total discounted system costs over the total analysis period. The solution pinpoints which technologies and energy carriers that are optimal under the constraints described.

MARKAL is coupled to a database, which must be supplied with all necessary data to describe the energy system of interest. This often includes all technologies and energy carriers used for supply, conversion and *end use*, the last in contrast to many econometric models. The model describes the resources, technologies and energy carriers connected to the energy system. All associated costs are summed up for the simulation horizon and discounted down to a base year. The discount rate is 7%, reflecting a long term national economic viewpoint. The total discounted system costs are then minimized with regard to a vector of technology capacities.

The assumption of perfect foresight and a discount rate of 7% might not be realistic for private industrial companies, and tends to overestimate the energy flexiblity. This is especially true for conservation measures, where most companies require 2-4 years payback. Accordingly, we have implemented separate hurdle rates for conservation measures on 30% (20% for some major measures).

The demands and the menu of technologies and energy carriers span a linear space of feasible solutions, within which the optimal solution must be found. Quantitative emission levels (e.g. CO_2) or other user specifications can also restrict the solution space.

For calculating the electricity balance each period is again split up in three seasons, which again is split up in a day and a night fraction. This makes it possible to incorporate varying prices over the year, as is the case on the Scandinavian Electricity Stoch Exchange (Nordpool). For example, the prices tend to be lower in the summer and during the night.

Model Data

The MARKAL pulp and paper model requires an extensive amount of input data. Projections for net energy demands, technology descriptions and statistics for energy use and production in the base year are the most important.

Information on installed energy conversion equipment was provided through a questionnaire, which was sent to all pulp and paper mills. In the questionnaire it was asked for information regarding boiler capacities, energy carriers, efficiencies, investment costs and operating and maintenance costs. All but one small mill answered the questionnaire (Rosenberg 1998), representing 98% of the sector's energy use.

Of the replies, everybody quoted their installed capacity of boilers and year of installation, but only one third stated the investment and/or the operation and maintenance costs. A summary of the survey is presented in table 1.

Even though there is a large diversity regarding year of installation, we can observe a general trend that many oil boilers are installed *before* the oil shock (1973). Electric boilers dominated from the beginning of the eighties, while bio-boilers have become more popular the last 5 years.

We calibrate and align the model with base year data from the "Industrial Energy Efficiency Network[2]". The network have data for energy use by product and fuel; both internal energy and purchased fuel. Specific consumption in the base year is found by performing an end use specification and dividing by production volumes.

Demand projections for average production and energy use in the sector have been taken from background figures for a green paper on long term Norwegian energy policy (OED 1998). The projections show a 50% increase in useful energy demand, from 1996 to 2020. In lack of other information we have assumed the same growth rate for every mill. Costs (investment and O&M costs) for steam turbines are based on national data (NVE 1996).

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[1] Four mills, which have been closed after 1996, are not included in the model.

[2] The "Industrial Energy Efficiency Network" aims at a better co-ordination of energy efficiency measures and activities among the member companies. The members annually report confidential energy and production figures to the network. Data are available from 1989 to 1999 per today, and all pulp and paper mills are members. The network is sponsored by the Norwegian Water Resources and Energy Directorate and administrated by Institute for Energy Technology.

Table 1. Key Data from the Special Questionnaire to the Pulp and Paper Mills

	Average					Total	
	Install. power MW	Boiler eff.	Year installed	Inv.cost US$/MW	OM/cost US$/MW	Number of boilers	Capacity MW
Electric boiler	23	96 %	1978	14	1.5	28	644
Oil boiler	30	88 %	1971	27	2.4	30	861
Bio boiler	32	89 %	1985	216	18	9	284
Boiler for black liquor	99	85 %	1977	-	9	4	395
Other boilers	19	-	1982	380	8	5	94
Steam turbines	16	-	1973	157	-	5	78

Biomass Module

Biomass is an important energy resource for the industry, and deserves a careful treatment. The mills can use both internal (own) biomass or acquire biomass from outside. Internal resources are considered to be available at no cost, because the alternative might be even more expensive (deposition) or even illegal due to environmental regulations.

In addition to internal fuels, the mills can acquire other biomass resources presently not in use. There are almost 40 PJ unused and easily accessible biomass in Norway (Saur, Raadal and Erstad 1998). These resources consist of hardwood, thinning wood, wreck wood, straw and by-products from the timber industry. The resources are unevenly distributed, and a large fraction is in the south – east counties. We have grouped the resources into 10 geographical regions.

The price for the resources will depend on costs for harvesting, transport and possible scarcity, i.e. competition with other usage of the same resources. For the time being we ignore the last option, and examine costs for harvesting and transport. For each region, we have divided the resources into 5 cost classes depending on conditions for felling, and calculate costs for transport separately.

Each mill can acquire biomass from any region, but the further away the region is, the more expensive it will be. Most of the mills are concentrated on the south-east coast. The resources in these counties are therefore more attractive than the resources in Western and especially in Northern Norway. Often it will be more attractive to use expensive (with regard to felling) resources in central regions than cheaper resources in remote areas, since transport

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costs generally are high. Import from Sweden is not considered even though this would be much more economical than using resources in Northern Norway.

Based on information from one of the enterprises in the data set we have made a linear model for the transport costs

$$Y = a X + b$$

where Y is the transport costs (USD/GJ) and X the transport distance (km). Making a least square fit of our data we have estimated *a* to 9.7 USD[4]/(TJ · km) and *b* to 320 USD/TJ. It would have been desirable to check the coefficients with data from other enterprises, but such data has not been available.

Analysis

Energy Prices and Flexibility

Electricity is mainly used for electricity specific end uses as elctric motors. This use can not be substituted. Thermal demand can be met by oil, biomass or electricity. In addition oil and biomass can be used for electricity production when electricity prices are sufficiently high.

Both for thermal and electric demand, we have included in the database measures for energy conservation. When these measures are found to be profitable, they so to speak replace the need for final energy. Since the menu of measures are not exclusive, the potential for energy conservation will probably be larger than calculated by the model.

In order to explore flexibility of energy use in the sector we have varied electricity and oil prices in a systematic manner. Fuel shares for steam production for various price levels are shown in Figure 1.

Use of Biomass and Black Liquor

Black liquor is a base load fuel and covers approx. 40% of thermal energy use regardless of energy prices. For low electricity and oil prices, the model do not reinvest in new boilers for black liquor after 2020. This might not be realistic as this is a convenient way of recovering chemicals.

Other biomass use (chips, bark etc) will cover from 20% to 50% of thermal energy demand. The bio boilers are generally newer than the boilers for black liquor, and it is not likely that the utilization will drop below the present level of 20% as long as the boilers are operative. In order to reach the 50% level, oil and electricity prices must exceed 0.6-0.8 cents/MJ (~2.2-2.8cents/kwh). This is almost twice the present price. When both oil and electricity prices increase, biomass use (exclusive black liquor) increase two or threefold, see Figure 2.

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[4] We have set 1 USD = 9 NOK (Norwegian Crowns).

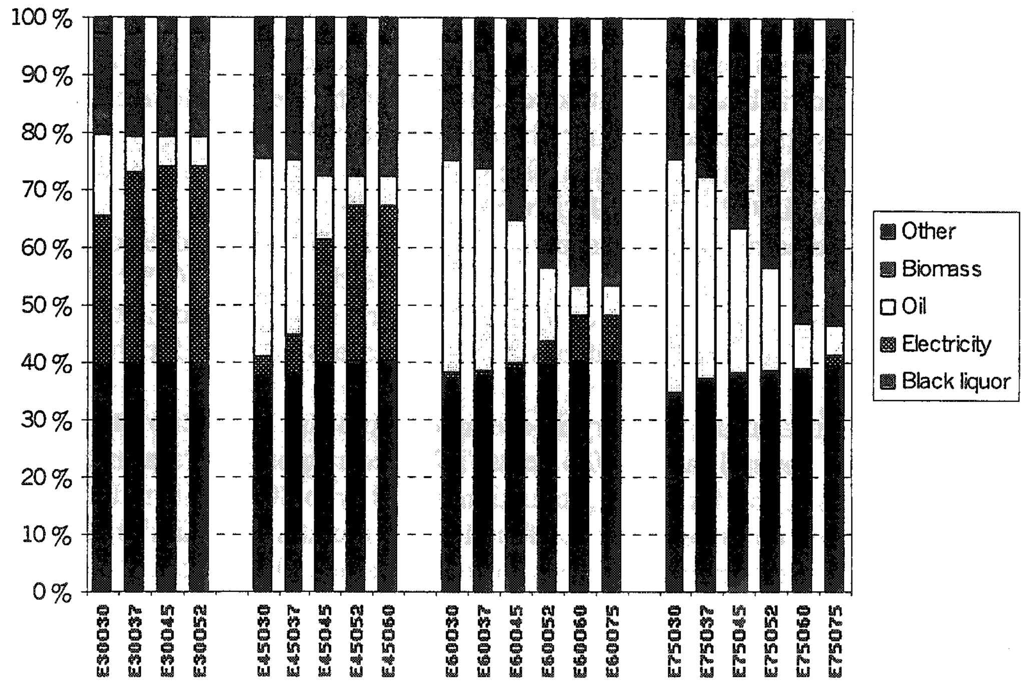

Figure 1. Fuel Shares for Steam Production with Varying Energy Prices (E60O40 means elprice 6.0 cents/MJ , oilprice 4.0 cents/MJ, etc...)

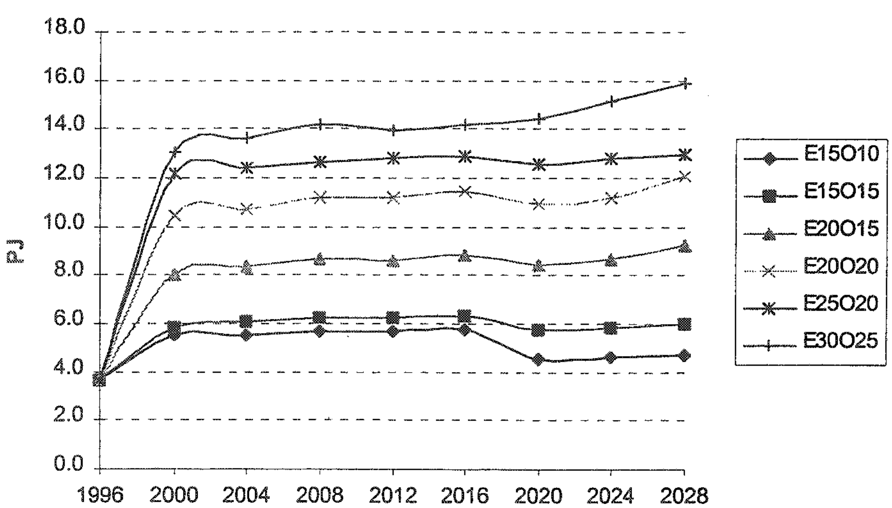

Figure 2. Use of Bio Energy with Varying Energy Prices (exclusive black liquor)

Use of Electricity for Steam Production

When electricity prices are lower than oil prices, and relatively low compared to prices for biomass, electric boilers might cover 30-40% of the thermal demand. On the other hand, when electricity prices are higher than 2.5 cents/kWh, electricity use for steam production is more or less given up. The electricity share for "normal" prices (electricity approx. 1.7 cents/kWh, oil 0.32cents/MJ) is approx. 10-15%.

The modelled electricity use is shown in Figure 3. The reduced electricity demand from the lowest to the highest price level is caused mainly (65%) by increased autoproduction but also reduced use of electric boilers (35%). Electricity conservation measures which are modelled in the database, are too expensive even for the highest price level.

Presently, manufacturing industry is exempted from the electricity tax. If the plants had to pay half of the general tax, i.e. 0.6 cents /kWh, corresponding to a price increase of 35%, electricity consumption for steam production would drop 80%. This reduction amounts to 200-300 GWh. Based on price elasticites found in the literature, we find that the potential for reductions for electricity specific purposes is of the same order in absolute numbers. The total reduction could be 10% in the long run, or approx 0.6 - 0.8 TWh.

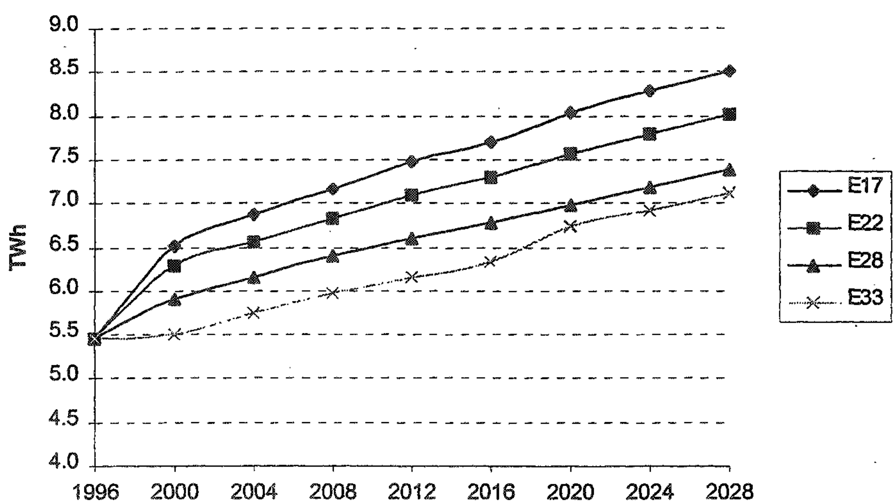

Figure 3. Electricity Consumption per Annum for Varying Electricity Prices (1.7-2.2-2.8-3.3 cents/kWh)

Use of Oil

When oil prices are much (more than 30%) lower than electricity prices and relatively low compared to prices for biomass, oil cover up to 30-40% of thermal demand. Biomass, black liquor and a small amount of electricity cover the rest. On the other hand, when oil prices are higher than 0.5 cents / MJ, oil use is more or less given up, except for direct use of oil. The normal level is 20-30%.

Presently the pulp and paper industry pay only half of the general CO_2 tax. If they had to pay full CO_2 tax (0.15 cents / MJ ~ 20 USD/ton CO_2), the fuel price would increase by 0.06 cents/MJ and oil use would decrease 13% immediately and 25% on long term. This is shown in Figure 4 as the "0.37 cents/MJ" graph.

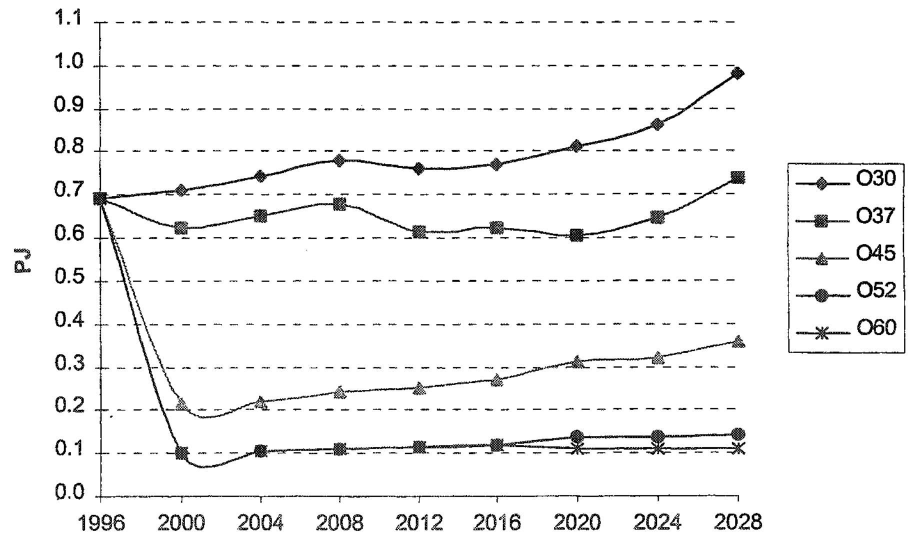

Figure 4. Fuel Oil Consumption per Annum for Varying Pil Prices (0.30-0.37-0.45-0.52-0.60 cents/MJ)

Electricity production from back pressure and condense turbines shows to be between 300-500 GWh for most realistic price levels. Increased electricity production from the bottom level is generally generated from oil or biomass in a number of different mills. Electricity production above 500 GWh requires investments in new turbines and multi-fuel boilers, and occurs only when the electricity price is at least twice the price of thermal energy, which is unrealistic for Norwegian conditions.

Investment Grants

Since 1997 the Norwegian Water Resources and Energy Directorate has administered a grant scheme for supporting investments in technology for increasing use of renewables, in particular bio-boilers. The average grant level has been approx. 20% of the total investment.

In the analysis of the importance of grants for more use of bio energy, the electricity price is set to 1.7 cents/kWh and the oil price to 0.32 cents/MJ, the approximate price level in 1998 and 1999. Based on these prices the model prescribes the use of bioenergy to increase by 50% on short term. This is in good agreement with data from the Industrial Energy Efficiency Network, which show that biomass use in 1999 had increased to 5.7 PJ, which is a 50-60% increase. Our impression is that the main reason for this was the favourable "climate" for biomass investments after the extreme dry years 1996/97 with high electricity prices.

The analysis reveals that biomass use could decline after 2020 if no grants are given. At this time, two turbines become too old to operate. One is never replaced without grants, the other is replaced with a turbine with higher efficiency. In both mills steam demand is reduced, and this affects biomass use, as biomass is the marginal resource in the two mills.

The subsidy will have largest effect on smaller mills, which have the highest unit costs, and most of them did not have any multifuel boiler previously.

According to our model the grant scheme (20% support) will secure an increase of 0.4PJ on short term (2004) and 1.4PJ on long term (2020) compared to the baseline projection, see table 2. Even for a 50% grant scheme, biomass use is not increased as much as when imposing taxes which increase both el and oil prices with 5 øre/kWh.

On the other hand most mills demand a higher rate of return than 7% on investments. Therefore the grant scheme could be more efficient in real life than what is shown by the model.

Table 2. Use of Bioenergy at Different Levels of Grants (PJ/year)

Scenario/year	1996	2004	2020
No grants	3.7	5.4	4.7
10% grant	3.7	5.4	4.7
20% grant	3.7	5.8	6.1
50% grant	3.7	6.5	6.5

Conclusion

The model of the Norwegian pulp and paper industry is used for prescribing energy flexibility on short and long terms.

Varying electricity and oil prices, we find that black liquor covers about 40% of thermal energy demand in almost all cases. Otherwise it would create a waste problem. Other biomass resources, mainly internal bark and chips in the mills, cover presently approx 20% of the thermal demand. Doubling electricity and oil prices, biomass share can increase to 50%, and more biomass has to be acquired outside the mills.

The electricity - oil ratio is very sensitive to minor price differences, but for low and reasonable prices their combined fuel share is relatively stable at 40%.

Investment grants for solid fuel boilers are not as efficient as higher electricity and oil prices, at least when applying a rate of return which reflects a long term national economic viewpoint.

Acknowledgements

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APPENDIX 1: Model Structure for Each Mill